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LASERS

by

Gus J. Caros

April 1964

Redstone Scientific Information Center

U S ARMY MISSILE COMMAND
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6 **LASERS**

10 by

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ABSTRACT

THIS STATE-OF-THE-ART SURVEY CONSISTS OF TWO SECTIONS, A TECHNICAL SUMMARY AND A BIBLIOGRAPHY. ALTHOUGH THE BIBLIOGRAPHY, WHICH CONSISTS OF 125 REFERENCES AND COVERS THE PERIOD OF 1 JANUARY 1963 TO 31 DECEMBER 1963 DEALS MOSTLY WITH THE SUBJECT OF LASER PUMPING, THE SUMMARY REVIEWS OTHER TOPICS OF LASER TECHNOLOGY INCLUDING A DESCRIPTION OF THE VARIOUS TYPES OF LASERS AND THEIR POTENTIAL APPLICATIONS.

FOREWORD

This document consists of two main sections, a technical summary and a bibliography on the subject of lasers. Since it was prepared in response to a request for specific information, it is unusual in some respects. The bibliography is mostly composed of recent references (since January 1963) and deals primarily with pumping techniques. The technical summary, however, reviews the entire field of laser technology, and it is hopefully anticipated that it will be found useful by those who are interested in a state-of-the-art survey on lasers.

The bibliography, which is mostly annotated, consists of 125 references arranged in alphabetical order by title. A personal author index for the bibliography is provided. The material was obtained from the several sources of information available at the Redstone Scientific Information Center (RSIC), which include the following:

a. RSIC holdings (books, reports, and journals).
b. NASA (a computer tape search of NASA tapes which contain references from the Scientific and Technical Aerospace Reports and the International Aerospace Abstracts).
c. Defense Documentation Center (DDC), (abstract cards of pertinent information furnished on request by the Defense Documentation Center, Arlington 12, Virginia).
d. Space Technology Laboratories, Inc., (a bibliography on Masers and Lasers by J. F. Price and A. K. Dunlap).
e. Applied Science and Technology Index.
f. Solid State Abstracts.
g. The Engineering Index.
h. Chemical Abstracts.
i. Cumulative Book Index.
j. U. S. Government Research Reports.

Searching of the above sources was mostly limited to the period of 1 January 1963 through 31 December 1963, although a few references dating prior to and after this period were also included because of their value in the preparation of the survey. Some references, although published in 1963, were not considered worthy of inclusion and are omitted.

As with most summaries, the technical summary is necessarily brief and the discussion rather general in nature. This approach was considered necessary because of the vastness of a subject such as lasers. This, however, should not detract from the value of the survey, because sufficient bibliographic references, especially in the area of laser pumping, are provided for those who desire more information. The author will be grateful for any remarks or suggestions. Comments may be addressed to the Redstone Scientific Information Center, Redstone Arsenal, Alabama.

TECHNICAL SUMMARY

Section I. INTRODUCTION

The word LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. Lasers are also referred to as optical masers, because the laser concept is an extension of MASER (Microwave Amplification by Stimulated Emission of Radiation).

The interest in lasers is so great that since the successful construction of the first laser by T. H. Maiman in 1960, well over 500 domestic and about 75 foreign organizations have entered the field. A listing of organizations active in the laser field as of the fall of 1963 appears in references 11 and 12.

The laser offers a means of producing high intensity light or infrared radiation that is highly monochromatic, coherent, and is emitted in almost perfectly parallel rays. In fact, the output radiation is so directional in nature, that if a laser were used in conjunction with a properly designed optical system, the divergence of the beam would be only about one foot for every 190 miles that the beam travelled. This would make possible a ¼-mile spot on the moon.[811]

Another notable feature of lasers is the extremely large power that can be generated in a very narrow wavelength range. Under certain operating conditions monochromatic bursts of millions of watts can be produced. Since the laser beam can be focused to an extremely small spot, the resulting power density is enormous. For example, the focused output of a 50-kilowatt infrared burst from a neodymium-in-glass laser has a radiant power density of the order of 10^{12} watts per square centimeter; this is about 100 million times the power density at the surface of the sun. Furthermore, since the electric field strength of an electromagnetic wave is proportional to the square root of its intensity, the field at the focus of the laser beam is millions of volts per centimeter.[85]

These unusual properties of lasers suggest a variety of applications. Perhaps the most promising potential of lasers comes from time coherence, a property which permits the exploitation of radio and microwaves for communications. Laser frequencies are millions of times higher than radio frequencies, and hence in theory are capable of carrying up to millions of times more information. In fact one single laser beam has in principle more information-carrying capacity than all the radio and microwave frequencies in civilian and military use combined.[85] Some of the potential applications of lasers as envisioned at the present time will be described later in greater detail.

Section II. GENERAL DESCRIPTION OF LASERS

HISTORICAL BACKGROUND

The concept of stimulated emission of radiation was first introduced by Einstein in 1917, although his theory did not predict the properties of the stimulated emission. A few years later, Dirac developed a theory that predicted the coherence and other properties of stimulated emission.[33]

The first published reference to the theoretical extension of maser operation to the optical portion of the spectrum was by A. L. Schawlow (Bell Telephone Laboratories) and C. H. Townes (Columbia University) at the end of 1958. A practical demonstration that this was possible was first reported by T. H. Maiman (Hughes Aircraft Corporation) in 1960. Dr. Maiman's optical maser produced a pulsed output of visible light from a ruby crystal device. Later that year operation of another solid-state device using trivalent uranium was achieved by P. P. Sorokin and M. J. Stevenson (IBM). By using a different type of optical maser, a gas discharge tube, A. Javan, W. B. Bennett, and D. R. Herriott, at Bell Telephone Laboratories in 1960, produced continuous emission at normal temperatures. Perhaps the biggest step forward was made in November 1962, with the virtually simultaneous announcement from General Electric, IBM, and Massachusetts Institute of Technology that an entirely new continuous-output optical maser had been developed. This was a gallium-arsenide semiconductor device of transistor proportions and its efficiency was stated to be in the region of 50 percent which is 10 to 20 times greater than that of the ruby laser.[50]

PRINCIPLE OF OPERATION

Modern physics explains that electrons around atoms cannot occupy all energy levels or "orbits," but they can exist in only certain discrete energy levels. For simplicity let us consider a simple material with two levels E_1 represented with the solid circle, and E_2 represented with the dotted circle in Figure 1.[29] Initially the electron is in the lower energy level E_1. It can be stimulated to jump to the excited state of energy E_2 by the absorption of a flash of light of an energy equal to the difference of the energies of the two levels ($E_2—E_1$). When it falls back or decays to the lower energy level E_1, it re-emits the same amount of energy that caused it to jump to the higher energy level, $E_2—E_1$, as a photon or bundle of energy in the form of a flash of light.

Most lasers are based upon the absorption of optical radiation over a band of wavelengths to excite electrons in the laser material to an excited state from which there is a rapid decay to a state possessing a much longer lifetime, called a metastable state. From this metastable state, the electrons normally decay to a lower energy state, emitting fluorescent radiation. If this lower energy state is the ground state, we have a three energy level system, or if it is a relatively unpopulated state lying above the ground state, it is called a four energy level system. An example of the three level system is ruby or chromium doped alumina, and of the four level system, a rare earth doped material or host lattice such as Nd^{3+} in calcium tangstate.

In stimulated emission or laser action, the electrons in the metastable state decay together in phase. In order to have this, there must be a population inversion (i. e., there must be more electrons in the metastable state than there are in the state to which the electrons decay). This leads to the practical difference between three and four level laser systems. In three level systems, since the electrons decay to the ground state, an inversion necessitates that more than half of the electrons must be in the excited state before the conditions are right for stimulated emission. In the four level system, the population of electrons in the metastable state must only exceed that of the relatively unpopulated levels to which the electrons must fall to produce stimulated emission. The energy required to excite or pump electrons to these

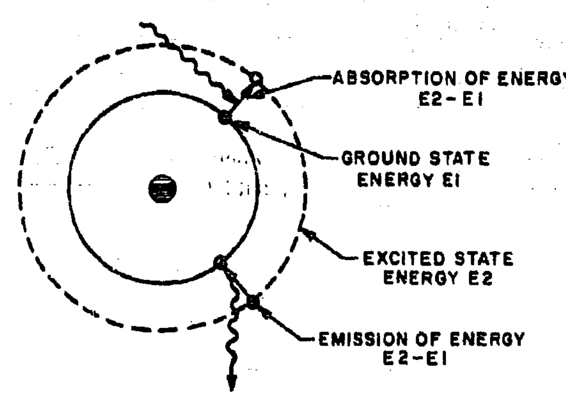

Figure 1. A Two-Energy Level Atomic System

higher energy levels is referred to as threshold energy. As a comparison of a three level system to a four level system, this threshold energy is 400 joules for ruby (a three level system), while for Nd^{3+} in calcium tungstate would be only 20 joules using similar excitation techniques.[29]

During the period in which the atom is excited, it can be stimulated to emit a photon if it is struck by an outside photon having precisely the energy of the photon that would otherwise be emitted spontaneously. As a result the incoming photon, or wave, is augmented by the one given up by the excited atom. The most remarkable fact, however, is that both photons, the one from the excited atom and that which triggers its release, fall precisely in phase.[96]

The basic requirement constituting a laser is a resonant cavity filled with a suitable active medium (Figure 2).[53] The principle of the Fabry-Perot interferometer is almost universally used for the resonant cavity. It consists of two carefully aligned parallel reflecting surfaces, the spacing between which is made equal to an integral number of half wavelengths at the required operating frequency, that is $d = \frac{n\lambda}{2}$. A light ray traversing the cavity is reflected at one end in the direction from which it came; it is then reflected at the other mirror in phase with the original ray, which is then reinforced. The active medium must be one which is capable of possessing at least two distinct energy levels corresponding to the desired output frequency. Furthermore, the properties of the medium must be such that it is possible to overpopulate the upper energy level of the substance with respect to the lower level or levels. A further necessity for successful operation of a laser is the provision of suitable and sufficient power to achieve population inversion.[50]

In Figure 2, the laser tube is silvered at one end (left) and partially silvered at the other. Photons are emitted when high energy atoms (black dots) fall to lower energy states (white dots). Many photons escape through the sides of the tube. Others build up in numbers by reflection at mirrors, until they emerge from the partially silvered end.

RUBY LASER[53]

The working element of a ruby laser is a cylinder of a pink ruby containing 0.05 percent chromium. The cylinder is usually between 1/2 and 1 cm in diameter and 2 to 10 cm long with plane end faces and parallel to a high degree of accuracy. One of the end faces is provided with a completely reflecting surface, while the other is partially reflecting. The ruby is irradiated on its side by light from a flash lamp operated for a few milliseconds at a time with an input energy of 1000 to 2000 joules. Most of the input energy is dissipated as heat; a fraction of it, however, is emitted by the flashlamp as blue and green radiation which is absorbed by the ruby providing the excitation. The ruby funnels the energy, which it absorbs over a broad spectral region, into a narrow emission line of the trivalent chromium ion around 6943 A. The radiation emerges coherently through the partially reflecting end of the ruby. A schematic diagram of a typical configuration of a laser is shown in Figure 3.

Actually, coherent radiation does not appear immediately at the beginning of excitation. At first, fluorescent radiation of about the same wavelength appears. This radiation arises by spontaneous transitions in the chromium ions of the ruby. Unless the exciting radiation is sufficiently intense, this fluorescent radiation will be the only one emitted from the ruby. When, however, the exciting radiation exceeds a certain threshold, coherent radiation appears through the end with the partially reflecting surface approximately 0.5 millisecond after the beginning of the irradiation.

Figure 4 is a diagram of a fluorescent solid with three levels of energy. The ground state, which is the lowest energy state, is denoted by horizontal line 1, the intermediate state by line 2, and the highest energy state by line 3. Stimulated transitions are indicated by W, spontaneous radiative transitions by A, and spontaneous non-radiative ones by S. The top levels in energy-level diagrams are shown as broad bands in contrast with the other levels. This breadth at the top level is a practical necessity because there is not enough energy available from ordinary sources of radiation in a narrow band. If a laser were used to excite another laser, then a material with a narrow top level would be acceptable.[55] Excitation is supplied to the solid by radiation of frequencies which produce absorption into level 3. Most of the absorbed energy is transferred by fast radiationless transitions into the intermediate level 2. The emission of radiation associated with the spontaneous return from level 2 to ground level is ordinary fluorescent. Such fluorescence will take place even at a low level of excitation. When the exciting radiation is sufficiently intense, it is possible to obtain more atoms at level 2 than are left at ground level. The spontaneously emitted photons traveling through the crystal will stimulate additional radiation, and thus induced emission is superposed on the spontaneous emission. Ruby lasers operate on a pulse basis and give quite high peak power output. Characteristically, pulses of the order of 10 kw output power and pulse durations of the order of 1 millisecond

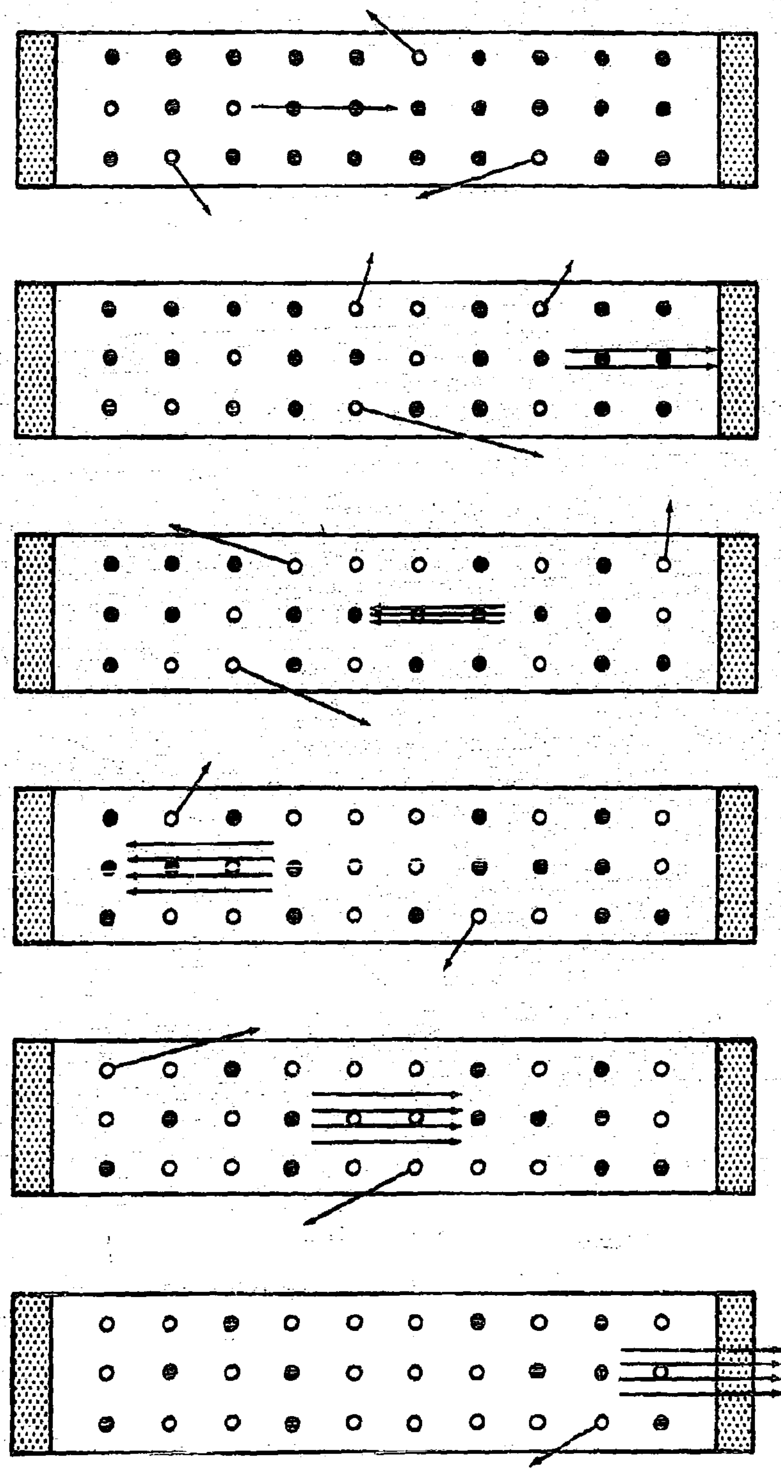

Figure 2. Fabry-Perot Resonator

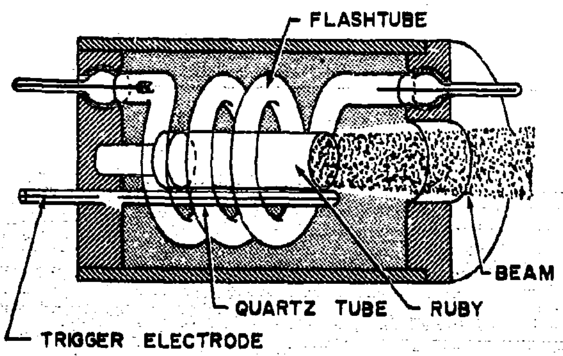

Figure 3. Ruby Laser

are obtained. The total energy per pulse is therefore on the order of 10 joules.[51]

FOUR-LEVEL LASERS

When the ruby is excited by a light flash, no laser output is obtained for the energy invested in removing, by excitation, one half of the atoms from the ground level. This inefficiency is an intrinsic property of every three-level solid laser. To overcome it, it is necessary to use a material possession four levels capable of participating in laser action. The schematic energy-level diagram of such material is shown in Figure 5. There is in this case an additional normally unoccupied level above ground level at which the relevant transitions terminate; therefore, laser action can begin as soon as there is significant occupation of the initial level, which in this diagram is represented by horizontal line 3. Sorokin and Stevenson constructed the first four-level laser, utilizing uranium or samarium ions embedded in a calcium fluoride crystal.[55] Other examples of four-

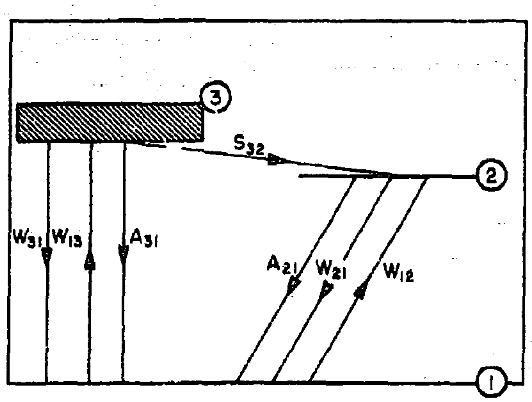

Figure 4. Energy-Level Diagram for a Three-Level Fluorescent Solid

level laser systems include trivalent neodymium in calcium tungstate and in certain glasses, divalent dysprosium in calcium fluoride, and trivalent uranium in strontium fluoride.[55]

Solid-state lasers generally operate intermittently. It is difficult to provide a sufficiently powerful source of exciting light capable of continuous operation and the necessary means of dissipating the great amount of heat which is generated during excitation.

In practice, four-level systems have much lower excitation power requirements, frequently less than 0.001 that of ruby. In some cases, such as in excellent, well-finished crystals of $CaWO_4:Nd^{3+}$, $CaF_2:U^{3+}$, and $CaF_2:Dy^{2+}$, laser action with output power measured in hundreds of milliwatts has been obtained for periods up to 30 minutes using a high intensity continuous light source for excitation. Continuous operation (commonly called CW, for continuous wave) at room temperature is a major objective of much research.[65]

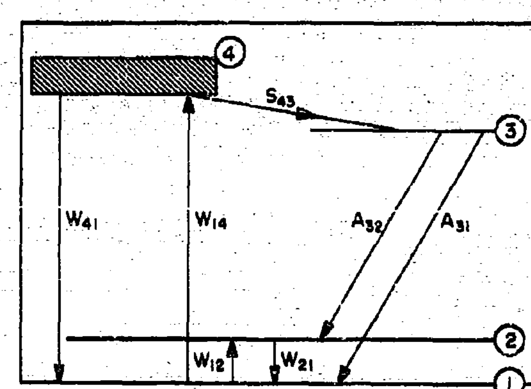

Figure 5. Energy-Level Diagram for a Four Level Fluorescent Solid

GAS LASERS

The first continuous wave and also the first gas laser was constructed during the fall of 1960 at Bell Telephone Laboratories by A. Javan, W. B. Bennett, Jr., and D. R. Herriott. A simplified diagram of this laser is shown in Figure 6. The laser consisted of a discharge tube 100 centimeters long with an inside diameter of 15 centimeters filled with helium at 1mm Hg pressure and with neon at 0.1 mm.[55] An RF (or dc) discharge is established in the gas mixture and the energetic electrons in the discharge excite helium atoms into a variety of excited states. In the normal cascade of these excited atoms down to the ground state, many collect in the long-lived metastable state 2^3S (See Figure 7).

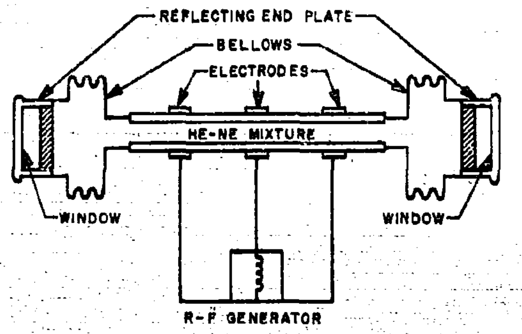

Figure 6. A Schematic of the First Gaseous Laser

It is primarily these excited metastable helium atoms which then excite the neon atoms up into the upper levels labeled 2S. They do this by colliding with unexcited neon atoms, and exchanging energy with them. The small difference in energy, about 0.04 volt in the case of the highest of the neon 2S levels, is taken up by kinetic energy in the colliding atoms. Thus, the helium atoms act as a funnel to convey the broad band of excitation (from the electrons) into a few sets of neon levels. The terminal laser level, or rather the set of possible terminal laser levels labeled 2p, decay radiatively to the metastable ls state in a time (0.01μsec) which is much shorter than the time for spontaneous decay of

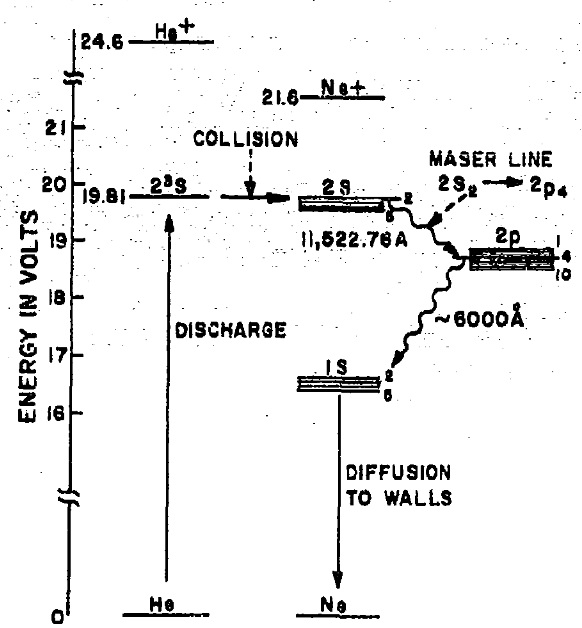

Figure 7. Energy-Level Diagram for H_e and N_e

the 2S down to the 2p levels (0.1μsec), so the conditions necessary for laser action are indeed satisfied. Other gaseous lasers include Argon, Krypton, Xenon, and Cesium-Vapor. The attractive feature of gas lasers is that they can be designed to produce output beams over a wide range of wavelengths. Moreover, such lasers operate continuously rather than intermittently. From the point of view of the details of the gas kinetics involved, these various gaseous devices may be classed under three headings. In the first of these, use is made of a mixture of two gases one of which is the laser material proper and the other an auxiliary medium that transfers power into the former through impact excitation. In the second, excitation is effected through electronic impact excitation in a gaseous discharge without an auxiliary atomic system. In the third, again using the laser material alone, excitation is purely optical arising out of absorption of photons from an incident radiation flux.[61]

In contrast to the more powerful crystal lasers, gas lasers are low-powered, but very pure spectrally and easily controllable. A gas-laser beam is at present the ultimate in coherence and uniformity. Applications of gas-lasers appear to be those which require precision rather than power, such as experimentation, standardizations, and demonstrations that depend on the utmost in controlled accuracy of radiation.

LIQUID LASERS

A liquid laser was constructed at Hughes Aircraft Co. using organic liquids. This laser operates on a principle called stimulated "Raman" scattering which has been observed in benzene, nitrobenzene, toluene, one-bromonaphthalene, pyridine, cyclohexane, and deuterated benzene. This laser is excited by a very strong incident light. It has proved expedient to excite liquid organic lasers with a high-power short-pulse ruby laser. The basic components of the Hughes Aircraft's liquid laser are shown in Figure 8.[9]

In February 1963, A. Lempicki and H. Samelson of the General Telephone and Electronics Research Laboratories reported a laser with europium benzoylacetonate in a solution of alcohol. The achievement was particularly surprising because one would expect the molecules in a liquid to be so buffeted by thermal agitation that the spectral emission lines would be broadened too much to sustain laser action. The europium ion, however, is not very sensitive to such buffeting, and is somewhat shielded by the outer portions of the chelate molecule. Almost simultaneously N. E. Wolff and R. J. Pressley at the RCA Laboratories announced operation of another europium chelate laser in which

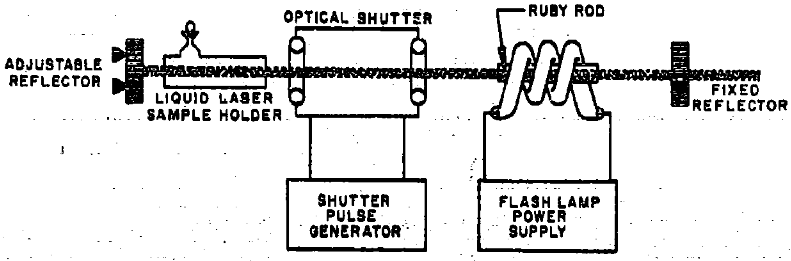

Figure 8. Liquid Laser

the chelate was suspended in an acrylic plastic. Liquid lasers provide more useful outputs than gasses, and are easier to handle than solids, which must be shaped. At the time of this writing, however, relatively little has been published concerning liquid lasers.

SEMICONDUCTOR LASERS

Undoubtedly the most interesting development has been the discovery of laser stimulated emission in semiconductors announced simultaneously in November 1962 by IBM, GE, and MIT.[81] Although the semiconductor laser is not intrinsically a high power device like the ruby or the glass laser, its power capacity as a continuously operating light source of more than one watt exceeds those of any other type. Its capability to be conveniently modulated at very high frequencies makes it an attractive candidate for applications in the field of communications. The extremely small size of the unit and its high efficiency in converting electrical energy to coherent radiation make it an ideal source of narrow band of energy for exciting lower frequency lasers in the far and near infrared and the submillimeter regions in a manner analogous to that of the more conventional three level maser in the microwave region.

The principle of operation of the semiconductor laser is best illustrated by the diagram shown in Figure 9, in which a diode is biased in the forward direction as shown. The effect of this is to produce an overlap of the two degenerate regions of the diode, namely the p- and n-type sides. The overlap regions are then characterized by two degenerate populations of electrons and holes at low temperatures in which the conduction band is filled to a level described by a quasi-Fermi energy F_c and the top of the valence band contains empty states to an energy of the quasi-Fermi level F_v below the top of the valence band. Under these conditions it can be shown that if the stimulated emission is to exceed the absorption for maser action to be possible, then $F_c - F_v > h\nu > E_g$ where $h\nu$ is the energy of the emitted photon and E_g is the energy of the forbidden gap in the semiconductor.[70]

By far the most fully developed injection laser is the gallium arsenide (GaAs) type, which operates at a wavelength of 8500°A when cooled to 77°K. However, at this time five other semiconductor materials, namely indium arsenide (InAs), indium phosphide (InP), gallium phosphide arsenide (GaPAs), gallium indium arsenide (GaInAs), and indium antimonide (InSb) have been successfully operated as injection lasers, and a silicon carbide device has been announced. The wavelength coverage of available injection lasers now extends from 6,500 A to 5.2 microns. Although lasers could be constructed from alloys such as $Ga(P_{(x)}As(1-x)$, where x is the percentage of phosphorous, in actual fact only a few spot wavelengths have been reported in the literature; GaAs at 8400 A (77°K), and 9,000 A (room temperature), InAs at 3.1 microns (77°K), InP at 9,000 A (77°K), GaPAs at 7,100 A (77°K), GaInAs at 1.77 microns (1.9°K) and InSb at 5.7 microns (1.7°K). Although both GaAs and InAs lasers have been operated continuously at liquid helium temperature (42°K), only the GaAs type has been operated continuously at liquid nitrogen temperature

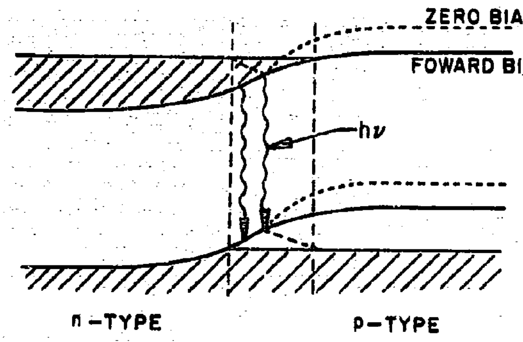

Figure 9. Energy Diagram of a Diode Laser with Forward Bias, Showing Overlap Region at the Junction, with Inverted Population Giving Rise to Stimulated Photon Emission

(77°K), and none except GaAs has been operated at room temperature. However, there is no fundamental reason why lasers such as the InP and InAs types cannot be operated similarly. At present, however, their lasing thresholds (required current density) are much higher than that of GaAs. Present lasing thresholds for Fabry-Perot type GaAs lasers are typically 1,000 to 2,000 amperes per cm^2 at 77°K, although values as low as 400 amperes per cm^2 have been realized.

Power outputs and efficiencies of injection lasers are strongly dependent on temperature. In liquid hydrogen (20°K) more than a watt continuous wave has been reported. The total overall efficiency (dc to light output) at 77°K is greater than 10 percent. This high efficiency as compared to that of other laser types is a principal advantage of semiconductor lasers.[80]

A detailed description of specific lasers is beyond the scope of this survey. The rapid growth of laser technology has led to generation of nearly 200 coherent optical and infrared frequencies in dozens of solids, liquids, and gases. A table of laser frequencies (reproduced from the January 1964 issue of Microwaves) is included in the appendix. The table was compiled through a survey of the literature and from correspondence with leading research organizations and reviewed by several scientists in the field. The table includes all the significant materials and wavelengths reported as of December 1963.[81]

Section III. PUMPING OF LASERS

BASIC THEORY

In general "pumping" is a process of raising matter from lower to higher energy; for example, raising the potential energy of water by moving it from an underground well to an elevated tank. In lasers, pumping refers to the process of raising atoms from a low energy level to a higher energy level.

To understand the principle of laser pumping, we shall consider a simplified atom with only three levels of energy A, B, and C (Figure 10). Levels A and B are low-lying and close together, and initially all the atoms are distributed equally between these levels as shown in Figure 10(a). Level C is much higher and the transitions A–C and B–C correspond to lines in the optical region of the spectrum. Suppose we radiate a sample of these atoms with a light beam from which the spectral line BC has been filtered. The beam contains photons that can excite atoms in level A but not in Level B. Atoms excited out of A absorb energy and rise to C. They remain there for a short time (as little as ten millionths of a second) and then drop back to A or B emitting energy. The proportions going to each energy level depends on the structure of the atoms, but the important thing is that occasionally an atom drops into B. When it does, it can no longer be excited by the incident light. If it returns to A, the light will raise it to C state again, and again it will have some probability of dropping to B. Given enough time, every atom will end up in the B energy level, and the material then is completely pumped. Referring to Figure 10, before pumping, the atoms are divided evenly between energy levels A and B, (a). After absorbing photons from a beam of light, (b), and after being raised to energy level C, atoms drop back in equal numbers to energy levels A and B, (c). As the process continues, only one atom is left at level A, (e); finally it, too, ends up in level B, (g). The atoms are then completely pumped.[24] Population inversion, which means raising more atoms to a higher energy level as compared with a lower energy level, is achieved through pumping (or excitation), and is a necessary condition to produce laser action.

PUMPING OF SOLID LASERS

OPTICAL PUMPING

One of the most popular methods of pumping or exciting a solid state laser is by illuminating it with a high-intensity light source, such as that produced by a xenon or mercury lamp, which induces an absorption transition in the laser material at a wavelength shorter than laser output transition. This technique can be used for either pulsed or continuous operation. Only in rare cases can lamps be found which emit only over a small wavelength interval which corresponds to the absorption band of a laser material. Instead, under conditions of maximum output, the spectral distribution of most gas-discharge lamps is quite broad (extending over several thousand angstroms in the visible spectrum). Since gas-discharge lamps are one of the most convenient and efficient sources of high-intensity optical radiation which have been developed to date, this means that for efficient utilization of the light available from these pumps, the laser material must have broad absorption bands.[122]

The basic fluorescent process and optical pumping can be understood by referring to Figure 11. With no excitation applied to the material the populations are as follows:

$$\frac{N_2}{N_1} = e^{\frac{-E_{12}}{kT}} \text{ and } \frac{N_3}{N_1} = e^{\frac{-E_{13}}{kT}}$$

Where N_1, N_2, and N_3 are the populations in levels 1, 2, and 3, respectively, E_{12} is the difference in energy between levels 1 and 2, E_{13} is the energy difference between levels 1 and 3, k is Boltzmann's Constant, and T is the temperature of the solid. When the material is excited by pumping light, ground state ions are excited to level 3. A nonradiative process then takes up some of the excitation energy and the ion drops back to level 2. The ion in level 2 has less energy than it initially received from the pumping radiation but, nevertheless, maintains the energy E_{12} with respect to the ground state. Since this situation represents a deviation from Boltzmann's equilibrium, the excited ion will return by some process back to the ground state. The two dominant mechanisms by which this can occur are either another nonradiative thermal process, or a radiative process known as spontaneous emission. This latter process is dominant in efficiently fluorescing materials.[68]

In summary, the fluorescent process consists of the following steps: First, pumping radiation causes absorption from level 1 to level 3. A thermal process takes up part of the absorbed energy leaving the ion in

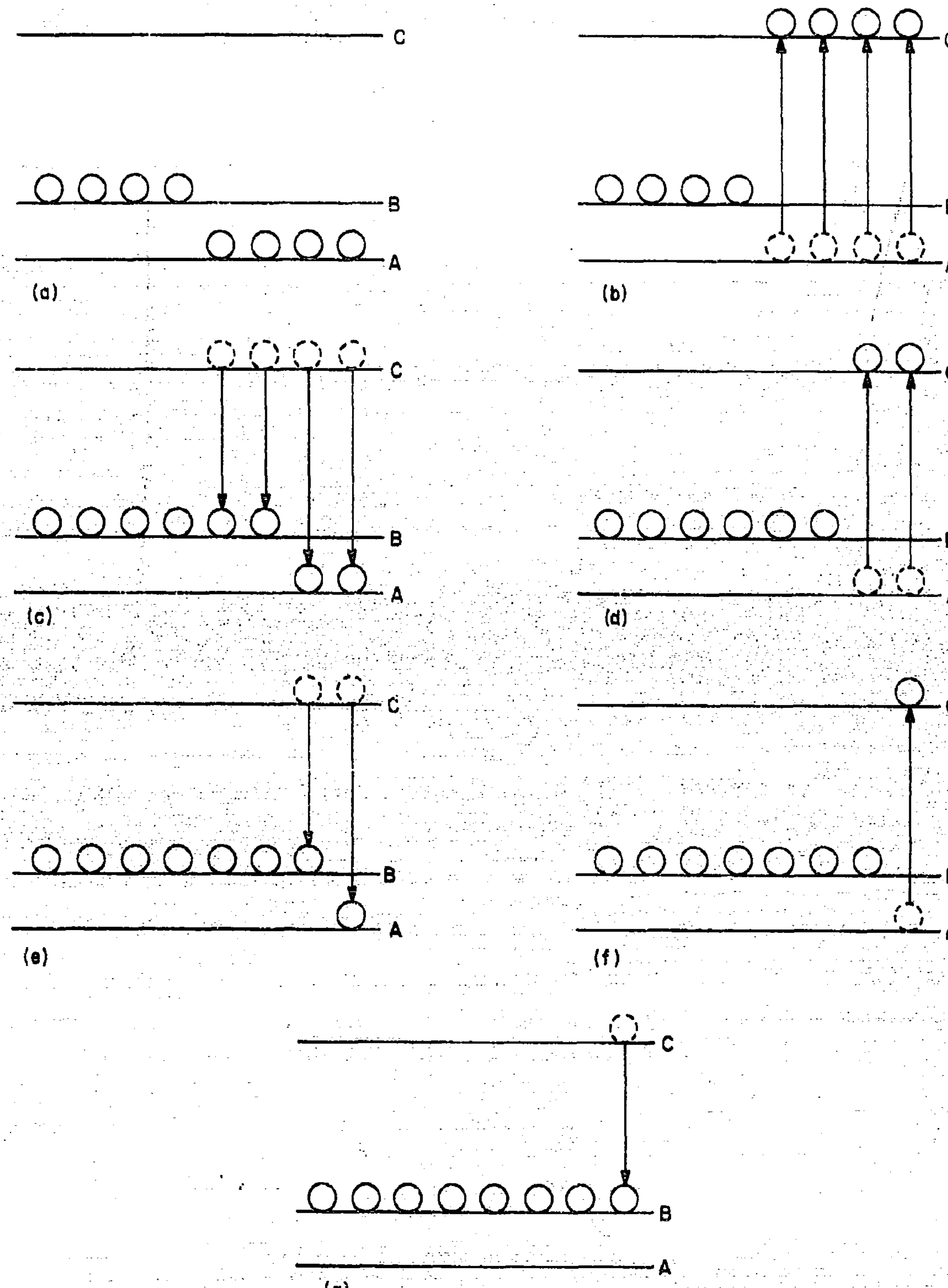

Figure 10. Pumping Process

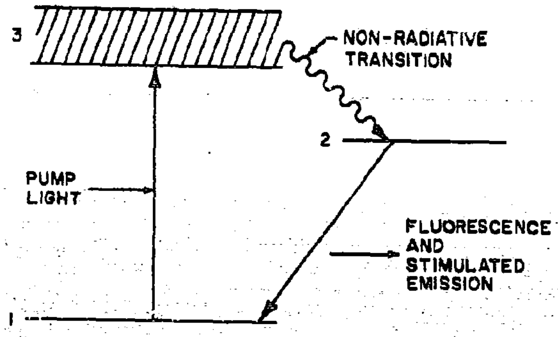

Figure 11. Energy-Level Diagram for a Three-Level Fluorescent Solid

level 2 (i.e., ground state ions are pumped indirectly to level 2). Finally, the ion returns to the ground state by spontaneously radiating the energy E_{12} as fluorescence.

The rate at which ions are pumped upward is equal to WN_1, where W is a factor directly proportional to the intensity of the pump light. The rate that ions decay from level 2 is AN_2, where A is the rate factor determining spontaneous emission, known as the Einstein A coefficient. Under steady state pumping, then, we must have

$$WN_1 = AN_2$$

thus, we obtain $N_2 > N_1$ only when $W > A$. Since we cannot obtain amplification until $N_2 > N_1$, the efficiency of a three-level pumping scheme is low unless W is much greater than A. In practice, however, making W much greater than A necessitates impractically high intensity pumping light levels. It is, in fact, very difficult to even reach the condition $W = A$. For this reason, three-level systems are not very practical for continuous operation, and ruby, which is a prime example of such a three-level system, is almost always operated under pulse excitation.[27]

Pulse excitation can be understood by again referring to Figure 11. The rate A is an inverse measure of the decay time of ions in level 2, or

$$\tau = \frac{1}{A}$$

where τ is referred to as the fluorescent lifetime. Thus, if a high energy pump pulse with duration less than τ is applied to the system, ions pumped up from the ground state will be stored in level 2. The total pump energy must be greater than $\frac{1}{2} N_1 E_{12} V$ in order to obtain $N_2 > N_1$ (V is the volume of the material).[83]

Due to the inefficiency of high pumping intensities required for three-level systems, another scheme, shown in Figure 12, is preferred. In this four-level scheme, level 1 is now high enough above ground state so that, at normal operating temperatures, $\frac{-E_{01}}{{}_{e}kT} << 1$ and thus level 1 is relatively empty. When pumping power is applied, ions are excited from the ground state indirectly to level 2, as in the three-level scheme, but now a comparatively small population need to built up in level 2 because it requires very little population in level 2 to have an excess with respect to the relatively empty level 1. Examples of a four-level system are Nd-glass and Nd-$CaWO_4$.

OPTICAL PUMPING ARRANGEMENTS

There are several techniques for surrounding the laser rod by the light source in order to produce as uniform excitation as possible. A commonly used arrangement was shown in Figure 3. The light source is arranged in a multi-turn xenon-filled quartz high energy helical flash tube and the laser rod is placed coaxially in the center of the helix. Although this is a convenient arrangement, pumping efficiency is rather low because of the large amount of light energy which is lost from the outer surfaces of the helix.[54]

Figure 13 shows another arrangement where the lamp and laser rod are both enclosed in an elliptical reflector. This type of arrangement has the advantage of concentrating the light on the rod.[122]

Another interesting approach to the problem of focusing as much light as possible into a small volume is by using the conjugate foci of several elliptical cylinders. Except for reflective losses, this method provides for almost 100 percent coupling between the light source and the laser rod. Figure 14 shows such an optical pumping arrangement which makes use of several light

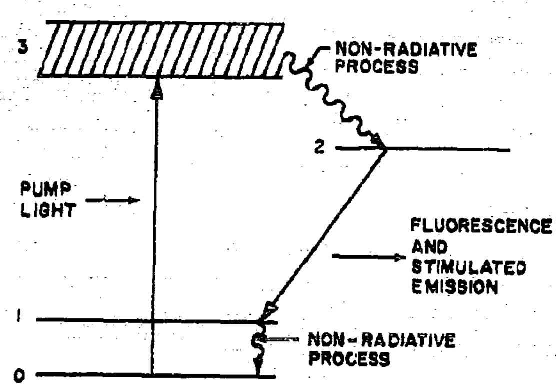

Figure 12. Schematic Diagram of a Four-Level Fluorescent Solid

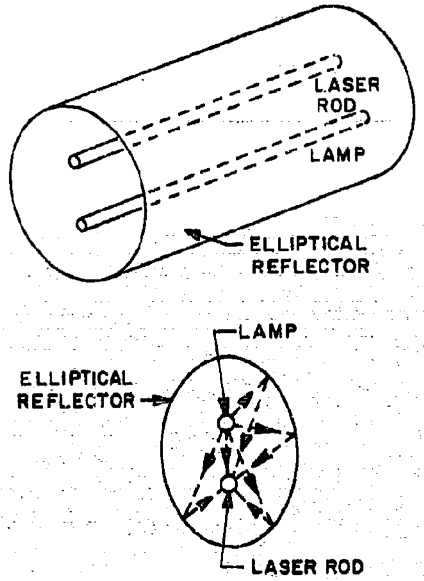

Figure 13. Pumping Arrangement Using Linear Lamp in an Elliptical Cylindrical Reflector

sources and several truncated elliptical cylinders (four in this case), all sharing a common focus which contains the laser rod.[82] In general, low optical excitation efficiencies are obtained (circa 1 percent) regardless of the arrangement employed because only a small fraction of the light emitted by the light source falls within the absorption band of the laser material.

Figure 15 shows a pumping scheme used by D. F. Nelson and W. S. Boyle to obtain continuous laser action in a ruby laser.[25] The high-intensity region of a short arc mercury lamp is imaged on the broad base of a trumpet-shaped rod with unity magnification. The light incident on the cone base is trapped by total

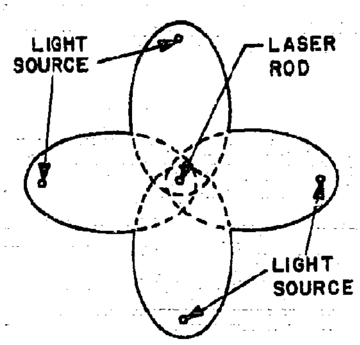

Figure 14. Four Ellipses Confocal Laser Pumping Configuration

internal reflection so that intensity at the ruby shank is larger than at the cone base by a factor which is equal to the ratio of the areas. The pumping radiation zigzags down the rod and after reflection from the far mirror retraces its path, thus, increasing the optical path length and consequently the absorption. The increased absorption plus the high intensity were sufficient to maintain continuous wave action at 77°K. It should be noted that the end-pumping scheme is especially advantageous for three level lasers. This is because the concentration of the active atoms must be kept low enough so as to ensure uniform pumping over the rod's

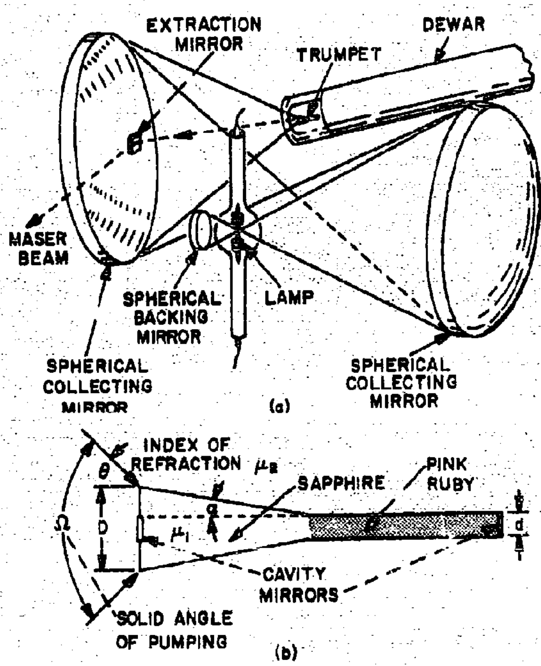

Figure 15. Ruby Continuous Wave Pumping Arrangement

length. Another pumping scheme for continuous laser has been proposed by J. Kremen. The method consists of using ellipsoidal mirrors for collecting a large solid angle of light and focusing it remotely with minimum image spread.[6] In addition to the use of high-intensity lamps, other sources of light include exploding wires, chemical reactions, nuclear energy, the sun, etc.

By exploding wires electrically, C. H. Church and his associates at Westinghouse Research Laboratories,[120] excited a 3-inch long, 0.25-inch in diameter ruby crystal to a room-temperature output of about 0.4 joules. The wire received about 14 kv from a 168-farad capacitor bank. The crystal, which was side-pumped in an elliptical cylindrical cavity, was encased in pyrex and plexiglass to protect it from an intense shock wave generated by a 50 to 100 μsec explosion (Figure 16). Tungsten, nichrome, aluminum, and copper wires were used in lengths of 2 inches and diameters of 8 to 15 mils. Exploding wires were found to be two to three times less efficient than xenon flash tubes in the visible spectrum, but more efficient in the ultraviolet portion of the spectrum. However, rise times were fast, and peak output powers of about 80 joules are predicted for improved versions of the system.[80]

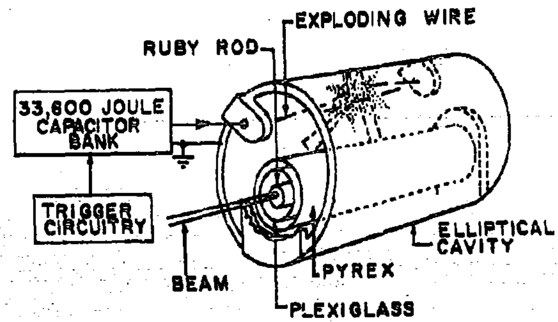

Figure 16. Exploding Wire Pumping Arrangement

Researchers at Westinghouse's Air Arm Division reported the near completion of a cathode-ray tube designed to excite its own ruby crystal by cathodoluminiscence. It has a special gun designed for electron optics and a longitudinally placed 4-inch long hollow crystal encased in a shield of Vicor. The gun's hollow beam strikes the inside of the cavity, which is coated with a manganese-doped zinc-ortho-silicate P_1 phosphor, and releases photons to the crystal. This pumping arrangement is shown in Figure 17. The tube is designed to convert a 1000-joule pulse into 40 joules of incident radiation on the ruby rod in 100 μsec at 200 amps and 50 kv. Continuous wave output is expected to be at least 100 watts for a 1000-watt input. Advantages of this method were listed as easy matching between phosphor emission and laser absorption bands; good conversion efficiencies, reaching 25 percent; high saturation radiance; relatively easy control of timing and intensity; ease of cooling, because the solid-state phosphor contacts the cooled surface; and high reflectivity allowing good coupling to laser crystals.[120] Pumping lasers by light from a shock wave caused by detonation of high explosive has been suggested as a way of achieving high laser output power and energy without the necessity of a large primary power storage system. Figure 18 shows the basic arrangement for pumping a neodymium-doped glass laser from a distance of 3½ meters without damaging the laser.[102] The explosive light source is placed behind a concrete wall pointing up into a mirror. This mirror directs the light horizontally into a plastic Fresnel lens which images the light source aperture, A, on the 60-cm diameter paraboloidal mirror. This mirror then forms an image of the Fresnel lens upon the laser rod.

Solar pumping of lasers was reported by G. R. Simpson of American Optical Co. at the 1962 Spring Meeting of the Optical Society of America.[80] A ruby rod one centimeter long and three millimeters in diameter was excited by using a 44-inch in diameter catadioptic paraboloid to focus the energy into an immersion optical system consisting of a menisus aplanat capable of a five-fold concentration, and an immersion hyperhemispherical aplanat of sapphire. A schematic of this arrangement is shown in Figure 19. Solar excitation of $CaF_2:Dy^{2+}$ was achieved by RCA Laboratories, and the details of this experiment are given in reference 120. Sun-powered lasers would permit direct sunlight to

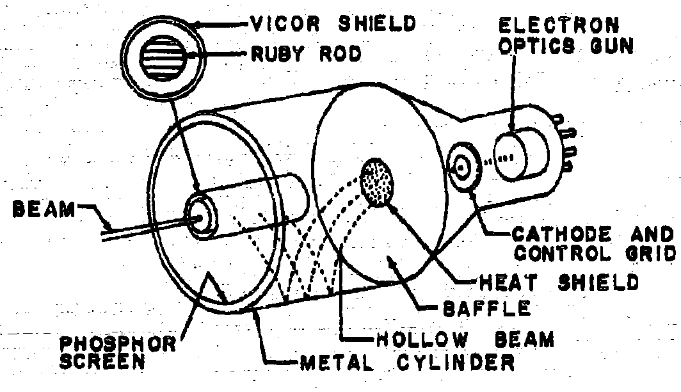

Figure 17. Excitation of Laser by Cathodoluminescence

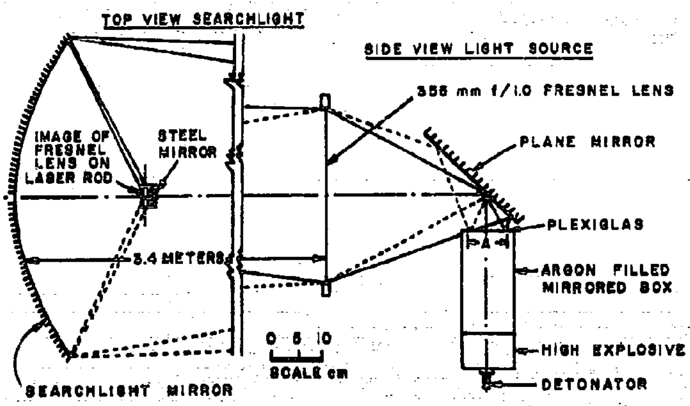

Figure 18. Arrangement for Laser Pumping by Explosive Light Source

power a system for communicating with satellites and other space vehicles. Use of the sun as a source of power will simplify the laser and provide a long-lived self-contained communications system.

Researchers at the Martin Company's Orlando Division are working toward the use of nuclear power to develop lasers capable of extremely high power and frequencies. At present, three basically different approaches are being applied. These are the use of atomic gases, the use of nuclear radiation to activate a laser crystal, and the development of self-activating laser crystals containing radioactive isotopes.[9]

The light intensities required to obtain continuous laser action can be estimated by using a method first employed by W. Kaiser et al.[110] If the energy flux per unit wavelength incident on the crystal is $I(\lambda)$, then the power per unit volume absorbed by the crystal is given by

$$\frac{P_{abs}}{V} = \int I(\lambda) K(\lambda) d\lambda,$$

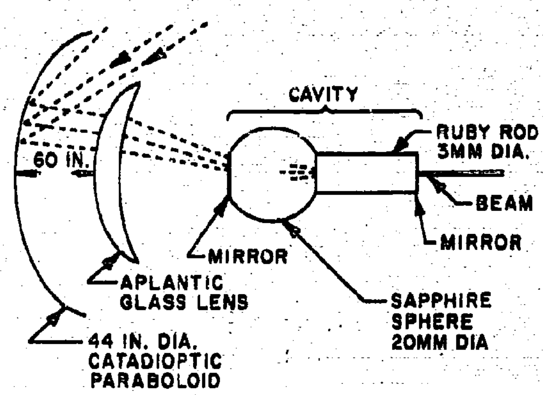

Figure 19. Solar Pumping

where the attenuation of $I(\lambda)$ is described by $I(\lambda, x) = I(\lambda, 0)e^{-K(\lambda)x}$ and the integration is over the useful absorption ranges. The equilibrium population of the metastable level established by the pump light is obtained by equating the rate of excitation (atoms per m^3 per second) to the rate of decay (assumed radiative)

$$\int \frac{\lambda I(\lambda) K(\lambda) \eta}{hc} d\lambda = \frac{N_2}{V t_{spont.}}$$

where V is the volume of the crystal and $\eta(\lambda)$ is the quantum efficiency for pump light at wavelength λ for exciting level 2. It is also assumed that K is small enough so that the decrease in I due to crystal absorption is small. By replacing N_2 by N_{2c} (i.e., N_2 at threshold), which for a four-level laser is equal to ΔN_c, we obtain an expression for the critical light intensity. If we replace I, K, and η by their average values for the useful absorption range $\Delta\lambda$ we can rewrite the above equation as

$$\frac{\lambda I K \eta \Delta\lambda}{hc} = \frac{\Delta\eta c}{V t_{spont.}}$$

Further details concerning this method of estimating the required light intensity for optical pumping as well as several numerical examples can be found in Reference 119.

The intense illumination required to pump lasers produces a considerable amount of heat which must be dissipated to prevent damage to the laser rod. Several cooling methods, such as optical cooling, are being investigated.[111] Plasma pinch excitation of a ruby laser has been proposed by R. A. Brandewie et al.[28] An unusually intense and well-defined output pulse was obtained from the ruby with apparently negligible heating of ruby or flash tube. The pump light was found to consist of line spectra rather than the blackbody continuum emitted by the xenon flash tubes. The theta plasma pinch configuration allows the important advantage of eliminating electrodes from the high current discharge tube. The flash tube consists of coaxial Vycor tubes, arranged to encircle the ruby rod with a theta pinch. The discharge is driven by a single-turn coil connected by a triggerable spark gap switch to a low-inductance capacitor.

Peak plasma currents exceeding 150,000 amps are obtained with this driver, which transfers approximately 35 percent of the initial stored energy into the plasma, the remainder being dissipated in circuit losses. Pronounced heating of xenon flash lamps is noted after firing with several hundred joules. For similar energy input the electrodeless flash tube produces no noticeable temperature rise, whether filled with xenon or argon. This unusual lack of heating is one of the most important advantages of electrodeless excitation. Although the detailed energy transfer mechanism is not well understood at present, it should be noted that the observed spectral energy distribution would be expected to produce significantly less heating than a blackbody distribution.

In summary, most attempts to increase power output in pulsed lasers, or to achieve continuous operation, seem to be taking the brute force approach of simply trying to get more pumping energy into the active material. Through a combination of high-intensity light sources and improved optical cavity geometry, researchers all over the country are literally blasting energy into laser crystals and serious problems of thermal cracking have been encountered. In many instances, ruby crystals have been blown apart with a single pulse of the input energy. While some progress has been made in terms of higher pulse rates and higher peak power outputs, the energy conversion efficiency has not improved significantly. A further limitation of this technique is the increasing requirement for extremely large power sources, which simply cannot be provided in any mobile application.

The ultimate approach to achieving significant improvements in power, efficiency, and lifetime of laser devices probably lies in the exploitation of nuclear sources for pumping energy. Some laboratory work is now in progress aimed at determining the feasibility of the several conceivable methods by which nuclear energy could be used in a laser system. In the Molecular Amplification Laboratories of the Martin Company in Orlando, Florida, two possible methods are being investigated. One involves the self decay of a gaseous isotope in a Fabry-Perot interferometer. A second method involves the direct irradiation of crystals by gamma rays, alpha particles, beta particles, or neutrons. This holds the promise of better power output, probably sufficient for a wide range of applications.[68]

EXCITATION OF GASEOUS LASERS

In gaseous laser materials it is possible to bypass the intermediate process of generating light by using collision processes in the gas. There are several different schemes for accomplishing this, which, although different in detail, all have the same basic process of collision excitation in common. In one family of gas lasers, of which the helium-neon laser is the archetype, a mixture of two gases is used. One of the gases (helium in this case) is chosen because it has a metastable state which coincides in energy with one of the excited states of the other gas in which the laser output transition occurs (neon in this case). This type of laser is excited by passing an electric current through the gas mixture. This heats the gas so that some of the atoms are ionized and electrons are freed. These electrons collide with the atoms of the first gas (called the exciting gas), and excite them to higher energy levels. As the atoms of the exciting gas decay to the ground state many of them will pass through the metastable level. Under some conditions of relative concentrations, the probability that exciting atoms will exchange their metastable energy with atoms of the laser gas in collisions can be made greater than the probability that they will decay to the ground state by other processes. Thus, the exciting atoms excite the laser gas atoms in very much the same way as the light in an optical excitation scheme. In gases, however, the absorption transitions are extremely narrow, therefore, direct optical pumping would be very difficult. The overall efficiency of the collision excitation method is quite low; maximum efficiencies of the order of 0.02 percent have been reported.

In another type of collision-excited laser only a single species of gas is required. This type of excitation has been used for pure helium, neon, argon, and krypton gases. This type of laser, as in the preceding case, is excited by either a radio-frequency or current discharge. The excitation of the laser gas atoms is believed to result from inelastic collisions between electrons freed by the discharge and the atoms. Selective excitation of the higher lying states of the atoms occurs because the cross sections for excitation of the levels differ from level to level.

A gas mixture is also used in still another type of gas laser; one of the gases changes the broad spectrum input energy into a narrow spectrum which can be used to excite the laser gas. In this case, however, the laser gas is molecular rather than atomic; when it is excited by collision with the exciting gas it dissociates into two atoms, one of which is in an excited state. The laser output transition occurs betwen levels in the excited atoms. Examples of this type of excitation scheme are $Ne–O_2$ and $A–O_2$ mixtures. The advantage of this scheme is that the molecular dissociation process can be excited by a broader spectrum of energies than atomic energy transfer.[122]

EXCITATION OF SEMICONDUCTOR LASERS

In semiconductor lasers, or junction-diode lasers energy states characteristic of the host lattice are involved in the lasing transition. These states, because of the overlap of the wave functions of the electrons in the atoms, are not discrete energy states or energy bands. The highest band filled with electrons is called the valence band and the next higher band is the conduction band. In a semiconductor these bands are separated by a region of energy in which there are no allowed states. Electrons can be excited from the valence band to the conduction band, leaving a hole in the valence band. The radiative transitions that can give rise to stimulated emission are caused by the recombination of these electrons and holes.[80] The probable mechanism for the process is that electrons pass from the conduction band of the n-type material through the junction barrier to a virtual level in the p-type material spectrum, and then make transitions to levels at the top of the valence band. If a sufficiently large current is passed, then an excess population in the upper level is created over that in the valence band and the conditions for laser action are established. Optical masers of this type are of considerable potential interest in the field of communications. Since the coherent radiation is generated by direct conversion of electric energy, then a modulated optical output may be produced by direct modulation of the exciting current.

The light emitted by the GaAs injected laser, which is a prime example of semiconductor lasers, is less coherent than that from a fluorescent solid laser. Typical values for one measure of coherence (frequency)/(line width in frequency units) are as follows:

gas	3×10^{11}
ruby	3×10^{7}
GaAs	3×10^{4}

Furthermore, the injection laser does not have the capacity to store large quantities of energy which can be released in a short pulse like the ruby laser. Thus, the semiconductor laser, by comparison, delivers low peak pulse power.

Section IV. POTENTIAL APPLICATIONS OF LASERS

When the transistor was invented in 1948 there was an obvious market for it. The trend towards miniaturization needed a miniature, reliable valve without complicated power supplies, and the transistor easily achieved great commercial success. Although the properties of lasers suggest a variety of applications, there was no ready market waiting for them. After four years of research, lasers have been confined to laboratory uses. A great many applications have been proposed, but the areas in which lasers might be fruitfully employed will be discussed here in rather general terms.

Lasers operating throughout the infrared, visible light and ultraviolet regions of the spectrum will find a variety of applications, and will possibly revolutionize communications and guidance techniques. Their employment within the earth's atmosphere appears to be subject to severe limitations because of atmospheric attenuation, but this will not affect their employment in the vacuum of space, where their potential is virtually unlimited.

Some medical uses have been proposed including repair of retina separation in the eye and the removal of cataracts. When the retina of the eye is torn or injured, it is possible to "weld" the retina to its support by coagulation with an intense spot light and thus prevent it from becoming detached. Preliminary tests on animals conducts at the Palo Alto Foundation and the Stanford University School of Medicine have shown how to regulate the output of the laser. If the device proves equally successful with human patients, it would enable the repair of retinal lesions.[101] Physicists also look forward to the laser as a tool for further study of the structure of the atom, and its beam may be useful in controlling delicate chemical reactions.

Military uses will be manifold, both on earth and in space. Optical radar systems will provide superior detection and target-seeking devices of extremely high resolution. Communications and guidance systems for space vehicles will not only be much more effective, but will be virtually undetectable. In comparison to microwaves, highly directional coherent light is less likely to be detected because of the smaller angular divergence of its beam.[98] A number of companies are under government contract to exploit the laser's potential as a military weapon. The principal area of interest is in missile defense. If a beam of sufficient intensity could be developed, a few bursts of laser light would knock down warheads or divert satellites from their course. Most of these projects are in their early stages of development, and significant technological advances will be required before they can be completed.

The output energy of a laser probably can be focused into an area so small that intensities of one hundred million watts per square centimeter and temperatures millions of times hotter than the sun can be produced. This, of course, opens up the posibility of innumerable processing and fabricating applications in manufacturing operations.[98]

It has been suggested that lasers may one day make "wireless" computers possible. Optical fibers, instead of wires, would transmit bits of information on a pulse of light. Such a computer would be faster than the present-day computer and would eliminate many problems with wires and transmission lines.

There are many optimistic references in the literature concerning future applications of lasers. The reader can be easily misled by such spectacular claims that the laser will be able to burn up intruding missiles in a Buck Rogers "death ray" fashion. It is true that a laser beam is capable of boring its way through a 1/8-inch thick steel plate in about 0.001 second; however, this technique would have to be extended by several orders of magnitude if it were to be used to remove large amounts of metal at a distance. Even if a conventional present-day laser system were scaled up by a factor of 10,000 it would only vaporize about one pound of steel.[40] The reader should keep in mind that the laser is still mainly an experimental device and many technical problems remain to be solved. Until the efficiency and the average output power (in contrast to the peak power) are increased, it will not be practical to use lasers for some military and industrial applications. The first applications will very likely be those in which some other property of lasers, such as high peak power or very monochromatic spectral output, is important.

APPENDIX

TABLE OF LASER FREQUENCIES[81]

TABLE OF LASER FREQUENCIES[a]

Wavelength (Microns)	*Laser Type*	*Materials*	*First Reported by*
0.2313[1]	Crystal	$Al_2O_3:Cr^{3+}$	Ford Motors Scientific Lab.
0.3125	Glass	Si Glass:Gd	Naval Research Laboratory (NRL)
0.3164[2]	Gas	He + Ne	Philco
0.323[2a]	Raman-Gas	H_2	Ford Motors Scientific Lab.
0.4175[3]	Semicon	GaAs:Zn	IBM
0.4650[4]	Semicon	SiC	Tyco
0.4905[2a]	Raman-Gas	D_2	Ford Motors Scientific Lab.
0.4942[2a]	Raman-Gas	CH_4	Ford Motors Scientific Lab.
0.5300[2]	Glass	Ba crown Glass:Nd	Lear-Siegler, Univ. of Mich.
0.5940[5]	Gas	He + Ne	Bell Telephone Labs. (BTL)
0.5985	Crystal	$LaF_3:Pr^{3+}$	Varian Associates
0.6046[5]	Gas	He + Ne	BTL
0.6118[5]	Gas	He + Ne	BTL
0.6118[6]	Gas	He + Ne	Spectra-Physics
0.6129	Liquid	EuB_3[7]	General Telephone & Electronics (GT&E)
0.6130		EuD_3 + "DMF"[8]	GT&E
0.6130	Plastic	Eu"TTA"[9]	Radio Corp. of America (RCA)
0.6293[6]	Gas	He + Ne	BTL
0.6293[6]	Gas	He + Ne	Spectra-Physics
0.6327	Gas	He + Ne	BTL
0.6328[5]	Gas	He + Ne	BTL
0.6328[10]	Gas	He + Ne	Spectra-Physics
0.6351[5]	Gas	He + Ne	BTL
0.6401[5]	Gas	He + Ne	BTL
0.6403[6]	Gas	He + Ne	Spectra-Physics
0.692	Crystal	$Al_2O_3:Cr^{3+}$	Hughes
0.6934	Crystal	$Al_2O_3:Cr^{3+}$	BTL
0.6943	Crystal	$Al_2O_3:Cr^{3+}$	Hughes
0.696	Crystal	$SrF_2:Sm^{2+}$	BTL
0.697	Crystal	$SrF_2:Sm^{2+}$	IBM
0.699	Crystal	$Al_2O_3:Cr^{3+}$	BTL
Note: Infrared spectrum begins at 7000 A			
0.7009	Crystal	$Al_2O_3:Cr^{3+}$	BTL and Varian
0.7041	Crystal	$Al_2O_3:Cr^{3+}$	BTL and Varian
0.708	Crystal	$CaF_2:Sm^{2+}$	IBM
0.710[11]	Semicon	$(GaAs_{1-x}P_x)$	GE
0.7306[5]	Gas	He + Ne	BTL
0.7431	Raman Liquid[12]	Deut. Benzene	Hughes
0.7456	Raman Liquid[12]	Benzene	Hughes
0.7457	Raman Liquid[12]	Pyridine	Hughes
0.7464	Raman Liquid[12]	Toluene	Hughes
0.7568	Raman Liquid[12]	Nitrobenzene	Hughes
0.7580[13]	Plasma	N	Services Electronic Research Lab. (England) (SERL)
0.7672	Raman Liquid[12]	Bromonaphthalene	Hughes
0.7673	Raman Liquid[12]	Orthoxylene	Hughes
0.7945[14]	Raman Liquid[12]	Elhyl Benzene	Hughes
0.7991	Raman Liquid[12]	Deut. Benzene	Hughes

TABLE OF LASER FREQUENCIES[31] (Continued)

Wavelength (Microns)	Laser Type	Materials	First Reported by
0.8053	Raman Liquid[12]	Benzene	Hughes
0.8053	nan Liquid[12]	Pyridine	Hughes
0.8350[8]	Semicon	GaAs:Zn	IBM
0.8400	Semicon	GaAs:Zn	IBM
0.8400	Semicon	GaAs:Te	GE
0.8440[15]	Semicon	GaAs:Zn	IBM
0.8446	Plasma	O (Also, Br + A)	BTL
0.8446	Gas	Ne + O_2	BTL
0.8470	Semicon	GaAs	ITT
0.8540	Raman Liquid[12]	Nitrobenzene	Hughes
0.8658	Raman Liquid[12]	Cyclohexane	Hughes
0.8683[18]	Plasma	N	SERL
0.8691[18]	Plasma	N	SERL
0.8698[18]	Plasma	N	SERL
0.8704[18]	Plasma	N	SERL
0.8710[18]	Plasma	N	SERL
0.8819	Raman Liquid[12]	Benzene	Hughes
0.8844[18]	Plasma	N	SERL
0.8847[18]	Plasma	N	SERL
0.8852[18]	Plasma	N	SERL
0.8856[18]	Plasma	N	SERL
0.8863[18]	Plasma	N	SERL
0.8871[18]	Plasma	N	SERL
0.8878	Raman Liquid[12]	Piperidine	Hughes
0.8879[18]	Plasma	N	SERL
0.8886[18]	Plasma	N	SERL
0.8893[18]	Plasma	N	SERL
0.8899[18]	Plasma	N	SERL
0.8909[18]	Plasma	N	SERL
0.9050	Semicon	InP:Zn	IBM
0.9223	Glass	Si Glass: Nd^{3}	Corning
0.9630	Raman Liquid[12]	Nitrobenzene	Hughes
0.9806	Raman Liquid[12]	Cyclohexanone	Hughes
0.9856	Raman Liquid[12]	Orthoxylene	Hughes
0.9864	Raman Liquid[12]	Acetone	Hughes
0.9865	Raman Liquid[12]	Orthoxylene	Hughes
0.9876	Raman Liquid[12]	Piperidine	Hughes
0.9876	Raman Liquid[12]	Metaxylene	Hughes
0.9876	Raman Liquid[12]	Orthoxylene	Hughes
0.9833	Raman Liquid[12]	Piperidine	Hughes
0.9886	Raman Liquid[12]	Piperidine	Hughes
0.9888	Raman Liquid[12]	Cyclohexanone	Hughes
0.9927	Raman Liquid[12]	1, 1, 2, 2, $C_2H_2Cl_4$	Hughes
0.9941	Raman Liquid[12]	Paraxylene	Hughes
1.034	Crystal	$SrMoO_4:Pr^{3+}$	BTL
1.018	Glass	$LiMgAlSi:Yb^{3+}$	NRL
1.037	Crystal	$SrF_2:Nd^{3+}$	BTL
1.039	Crystal	$CaWO_4Pr^{3+}$	BTL
1.042	Crystal	$LaF_3:Nd^{3+}$	BTL
1.045	Crystal	$CaF_2:Nd^{3+}$	BTL
1.0449[18]	Plasma	N	SERL
1.0455	Plasma	SF_6	BTL
1.0461[13]	Plasma	N	SERL
1.047	Crystal	$SrF_2:Nd^{3+}$	BTL
1.0472[13]	Plasma	N	SERL
1.0480[18]	Plasma	N	SERL
1.0491[18]	Plasma	N	SERL
1.0495[13]	Plasma	N	SERL
1.05	Crystal	$CaF_2:Nd^{3+}$	BTL
1.0505[13]	Plasma	N	SERL

TABLE OF LASER FREQUENCIES[a] (Continued)

Wavelength (Microns)	Laser Type	Materials	First Reported by
1.058	Crystal	$CaWO_4:Nd^{3+}$	BTL
1.058	Glass	Ba crown glass:Yb	NRL
1.059	Crystal	$SrMoO_4:Nd^{3+}$	BTL
1.059	Crystal	$PbMoO_4:Nd^{3+}$	American Optical Company
1.06	Glass	$LiMgAlSi:Nd^{3+}, Yb^{3+}$	NRL
1.06	Glass	Kodak Optical Glass	—
1.060	Crystal	$SrWO_4:Nd^{3+}$	BTL
1.060	Crystal	$SrMoO_4:Nd^{3+}$	BTL
1.060	Crystal	$CaWO_4:Nd^{3+}$	BTL
1.060	Crystal	$PbMoO_4Nd^{3+}$	BTL
1.061	Crystal	$CaWO_4:Nd^{3+}$	BTL
1.061	Crystal	$SrMoO_4:Nd^{3+}$	BTL
1.061	Crystal	$SrWO_4:Nd^{3+}$	BTL
1.062	Crystal	$CaWO_4:Nd^{3+}$	BTL
1.0628	Gas	SF_6 + He	BTL
1.063	Crystal	$SrMoO_4:Nd^{3+}$	BTL
1.064	Crystal	$SrWO_4:Nd^{3+}$	BTL
1.064	Crystal	$SrMoO_4:Nd^{3+}$	BTL
1.064	Crystal	$BaF_2:Nd^{3+}$	BTL
1.064	Crystal	$CaWO_4:Nd^{3+}$	BTL
1.064	Crystal	$CaWO_4:Nd^{3+}$	BTL
1.064	Crystal	$LaF_3:Nd^{3+}$	BTL
1.065	Crystal	$SrMoO_4:Nd^{3+}$	BTL
1.065	Crystal	$CaWO_4:Nd^{3+}$	BTL
1.066	Crystal	$CaMoO_4:Nd^{3+}$	BTL
1.0682	Plasma	SF_6	BTL
1.0689	Plasma	CO	BTL
1.116	Crystal	$CaF_2:Tm^{2+}$	RCA
1.119	Gas	He + Ne	BTL
1.125	Crystal	$CaF_2:Tm^{2+}$	BTL
1.152[18]	Gas	Ne	BTL
1.153[16]	Gas	He + Ne	Spectra-Physics
1.153	Gas	He + Ne	BTL
1.160	Gas	He + Ne	BTL
1.198	Gas	He + Ne	BTL
1.207	Gas	He + Ne	BTL
1.2303[13]	Plasma	N	SERL
1.2312[13]	Plasma	N	SERL
1.2319[13]	Plasma	N	SERL
1.2334[13]	Plasma	N	SERL
1.2347[13]	Plasma	N	SERL
1.3588	Plasma	N	BTL
1.4539	Plasma	CO_2	BTL
1.4544	Plasma	NO	BTL
1.529	Gas	Hg	BTL
1.612	Crystal	$CaWO_4Er^{3+}$	RCA
1.618	Gas	A	BTL
1.62[11]	Crystal	MgF_2:Ni	BTL
1.690	Gas	Kr	BTL
1.694	Gas	Kr	BTL
1.694	Gas	A	BTL
1.77[18]	Semicon	$(In_{.2}Ga_{.8})$As:Zn	MIT
1.784	Gas	Kr	BTL
1.793	Gas	A	BTL
1.813	Gas	Hg	BTL
1.819	Gas	Kr	BTL
1.91	Gas	Kr	BTL
1.911	Crystal	$CaWO_4:Tm^{3+}$	BTL
1.921	Gas	Kr	BTL

TABLE OF LASER FREQUENCIES[a] (Continued)

Wavelength (Microns)	*Laser Type*	*Materials*	*First Reported by*
1.95	Glass	$LiMgAlSi:Ho^{3+}$	NRL
1.974	Crystal	SrF_2Tm^{2+}	BTL
2.026	Gas	Xe	BTL
2.048	Crystal	$CaWO_4:Ho^{3+}$	BTL
2.060	Gas	He	BTL
2.062	Crystal	$CaWO_4:Ho^{3+}$	BTL
2.062	Gas	A	BTL
2.07	Semicon	$(In_{16}Ga_{84})As:Zn$	MIT
2.094	Crystal	$CaF_2:Ho^{3+}$	BTL
2.102	Gas	Ne	BTL
2.116	Gas	Kr	BTL
2.189	Gas	Kr	BTL
2.74	Crystal	$CaF_2:U^{3+}$	BTL
2.360	Crystal	$CaF_2:Dy^{2+}$	RCA
2.407	Crystal	$SrF_2:U^{3+}$	BTL
2.479	Crystal	CaF_2U^{3+}	IBM
2.500	Crystal	CaF_2U^{3+}	IBM
2.604	Gas	He	BTL
2.609	Crystal	BaF_2U^{3+}	MIT
2.613	Crystal	CaF_2U^{3+}	IBM
3.117(19)	Semicon	InA:Zn	MIT
3.199(20)	Gas	Cs	TRG
3.236	Gas	Hg	BTL
3.39	Gas	He + Ne	Spectra-Physics
3.437	Gas	Hg	BTL
5.2(21)	Semicon	InSb:Te	MIT
7.058	Gas	Kr	BTL
7.180	Gas	Cs	TRG
8.446	Plasma	Br + A	BTL
8.683	Gas	N_2	BTL
10.234	Gas	A	BTL
18.506	Gas	He	BTL
34.552	Gas	Ne	BTL
−52.00	Gas	Ne	BTL
485.5(22)	Gas Maser	Nd^{a}	Martin

(1) Produced as a third harmonic from ruby's second harmonic of 0.3470μ. Ford has also produced many lines between 0.2313 and 2.5μ by four-photon techniques, by frequency mixing, and by a combination of the two methods.

(2) Second harmonic coherent emission.

(2a) Achieved through Raman scattering induced by coherent pulses from a 6943-μ ruby laser. The figure shown is the shortest wavelength component of an output spectrum which includes several other frequencies.

(3) Cw version of IBM's pulsed semiconductor lasers. The 0.4175-μ second harmonic has been detected by IBM directly from the junction.

(4) Whether this is an actual laser emission is still unresolved at this time.

(5) Achieved through mechanical suppression of unwanted oscillations in a multimode laser.

(6) Mechanically tuned.

(7) Europium ion in trisbenzoylacetonate molecule, a chelate in alcohol form. Also described as an adduct of piperidine and benzoylacetonate.

(8) Europium dibenzoylmethide chelate with dimethylformamide.

(9) Phenoyl trifluoro acetonate chelate in polymethyl methacrylate plastic, reportedly a laser material.

(10) One version emits on 1.153 and 3.39μ.

(11) Also operated at several hundred wavelengths down to 0.6600μ, and believed capable of reaching 0.6000μ; emission wavelengths of semiconductor lasers are temperature dependent.

(12) Coherent emission resulting from Raman scattering induced by pulsed ruby laser emission into an organic liquid.

(13) One of many wavelengths produced from polyatomic molecules through dissassociation excitation transfer, first used by BTL, and indicated here by "plasma."

(14) Principal wavelength among 7 Raman lines.

(15) This is an np junction device.

(16) More than 130 other wavelengths have been produced from noble gases at BTL; these range in Ne from 1.152 to 34.55μ; A, 1.61 to 26.9μ; Kr, 1.69 to 7.058μ; Xe, 2.026 to 18.506μ; and He, 206μ.

(17) Radiative transition is phonon assisted.

(18) Different compounds of (InGa) as are believed capable of emitting at from 0.84 to 3.1μ.

(19) Also magnetically shifted to 3.125μ.

(20) Achieved with a Q-spoiling filter on TRG's 7.18-μ optically pumped laser.

(21) Operates only in a magnetic field but is magnetically tunable.

(22) Highest microwave maser frequency.

ANNOTATED BIBLIOGRAPHY

1. Academy of Sciences, Physics Institute, Moscow, USSR, "Coherence and Time Scanning of the Emission Spectra of a Ruby Laser," Korobkin, V. V. and A. M. Leontovich, Zhurnal Eksperimental' noi i Teoreticheskoi Fiziki, Vol. 44, pp. 1847–1851, June 1963. Soviet Physics—JETP, Vol. 17, pp. 1242–1245, December 1963. (A Translation)

Experimental investigation of the coherence of ruby laser radiation over the entire end surface, in order to explicate the nature of the time dependence of the excitation of these modes. The spectra and beam divergence in separate pulses were studied at −165°C. The radiation coherence was investigated by observing the interference of the radiation with a Michelson interferometer that had one of its mirrors replaced by a prism. Time scanning of the generated radiation was carried out with a type SFR fast camera operating as a photorecorder. The scanning shows that, in the individual bursts, generation occurs in several modes having different axial characteristics. The emission of excited modes is not propagated in a single direction as it would be in a plane-parallel resonator, but in a certain set of directions with a total divergence of 30 to 40 feet.

2. Aerospace Information Div., Washington, D.C., "Stimulated Emission from Organic Molecules with Possible Laser Applications," AID Rept. No. P. 63 85, 17 June 1963. AD-407 046.

3. Air Force Cambridge Research Labs., Bedford, Mass., "Lasers—A Basic Discussion of Types, Properties, and Principles," Stickley, C. Martin, Report No. AFCRL-63-1, January 1963. AD-401, 888.

This report describes the basic aspects of a laser. It includes a quantitative discussion of the major properties and the different types of lasers, as well as the basic laser mechanism—stimulated emission. Not included are detailed discussions of items that will be soon outdated. Several applications are presented in order to illustrate the properties of the laser.

4. Akademiia Nauk, Fizicheskii Institut im. Lebedeva, Moscow, USSR, "Primenenie Opticheskogo Kvantovogo Generatora Dlia Vozbuzhdeniia Rekombinatsionnogo Svecheniia V Poluprovodnikakh," Application of an Optical Maser to the Excitation of Recombination Luminosity in Semiconductors) Basov, N. G., L. M. Lisitsyn, and B. D. Osipov, Doklady, Vol. 149, pp. 561–562, March 21, 1963. (In Russian)

Investigation of the recombination luminosity of germanium, silicon, and gallium arcenide, at high excitation levels, using a ruby laser with a wavelength of 6934A and a light-pulse duration of 200 μsec. The experimental procedure is described, and oscillograms of the recombination-radiation pulse and the excitation-light pulse are presented. The use of a laser with light pulses of a duration of the order of 10^{-7} sec is recommended in future investigations of the kinetics of recombination processes.

5. Akademiia Nauk, Fizicheskii Institut im. Lebedeva, Moscow, USSR, "The Use of a Laser for the Excitation of Recombinational Radiation in Semiconductors," Basov, N. G., L. M. Lisitsyn, and B. D. Osipov, Doklady, Vol. 149, pp. 561–562, March 1963, Soviet Physics—Doklady, Vol. 8, pp. 290–291, September 1963. (A Translation)

Investigation of the recombinational radiation of Ge, Si, and GaAs at high levels of optical excitation by ruby lasers. It is found that at the temperature of liquid nitrogen (78°K) the intensity of the recombinational radiation is about orders higher than that at room temperature. The intensity at liquid helium temperature (4°K) is about two or three times higher than at room temperature. The spectra of the radiation of Ge at liquid He and Ni temperatures is given, and it is noted that the results for Si and for GaAs are analogous.

6. American Instrument Co., Inc., Silver Springs, Md., "Proposed Pumping Scheme for Continuous Laser," Kremen, Jerome, Applied Optics, Vol. 1, pp. 773–774, November 1962.

Description of four laser illuminator schemes. The optimum method, by incorporating a spherical mirror, collects almost a full solid angle of light from a lamp. If, in addition, the ruby is sapphire clad and the rear of the cladding is silvered, the image may be reduced and double-passed through the rod.

7. American Optical Co., Southbridge, Mass., "Neodymium Glass Laser," Snitzer, Elias, Paper presented at the Third Intern. Symp. on Quantum Electronics, Paris, Report No. AROD-3209-2, February 1963, Contract DA-19-020-ORD-5575.

The properties of the neodymium glass laser in high power and in fiber configuration are discussed. The results are presented of recent experiments on spectral pumping efficiency, output as a function of time, influence of the glass base containing the neodymium and spectral output.

8. Anonymous, "Laser Pumping may Bridge Submillimeter Gap," Electronics, Vol. 35, No. 26, pp. 7–29, June 1962. Hughes Research Labs. last week announced development of an experimental laser-pumped maser. Its optical pumping principles, Hughes said, can lead to devices operating in the submillimeter region between microwaves and the lowest laser frequency, 30,000 Gc.

The Hughes maser uses ruby. Its operating frequency is 22.4 Gc, outside the 200-30,000 Gc gap, but Hughes says the discovery of materials suitable for those frequencies may now be "confidently expected." The company says that efforts to increase maser frequency have been hampered by the unavailability of pumping sources in excess of 150 Gc, limiting maser frequency to 400 Gc. Optical pumping, Hughes said, extends the pumping range by three orders of magnitude.

The maser cavity is a waveguide length loaded with ruby to act as a reflection cavity resonant at 22.4 Gv. Placed in a magnetic field and pumped by ruby laser beam, it exhibited amplification and emission at 22.4 Gc, Hughes reported. The experiments were performed by D. P. Devor, Jr., I. J. D'Haenens and C. K. Asawa, under a $100,000 one-year contract with the Signal Corps.

9. Anonymous, "Laser Technology Explodes—New Develop ments Unveiled at Fast Pace," Electronic Engineering, Vol. 82, pp. 41–43, January 1963.

10. Anonymous, "Raman-Effect Laser uses Organics," "Electronic Design, Vol. 11, No. 2, pp. 28–29, 18 January 1963.

11. Anonymous, "A Directory of Laser Organizations," Semiconductor Products, Vol. 6, pp. 48–50, 56–62, August 1963.

    Listing of approximately 150 organizations active in the laser field. These organizations are listed alphabetically within the following categories: (1) laser suppliers; firms that manufacture and supply lasers, (2) laser materials suppliers; firms that supply crystals, glasses, chemicals, and other materials suitable for laser action, (3) laser accessory equipment suppliers; companies that offer power supplies, modulators, demodulators, instruments, and optical and other accessories used in laser systems, (4) laser research and development groups; organizations that seek to perfect lasers as components in various systems and programs or investigate the use of lasers as tools of research and production.

12. Anonymous, "Directory of Foreign R&D Laser Organizations," Semiconductor Products, Vol. 6, p. 9, September 1963.

    A listing of foreign organizations active in the laser field.

13. Anonymous, "Laser Pumping Technique," Science News Letter, Vol. 84, No. 12, p. 182, 21 September 1963.

    The Air Force has received rights to an internal pumping technique for use in lasers.

    Lasers, which produce a very narrow beam of intense light, ordinarily use an external gas-filled flash tube to irradiate light on the transparent laser crystal and "pump" the atomic system from a low to a high level.

    Under U.S. patent 3,102,920, invention of Janis A. Sirons of Springfield, Ohio, an internal electric arc or plasma provides the "pumping" source, allowing a coolant to pass over the outer surface of the crystal. This coolant ensures a greater emission of light radiation when the system is suddenly dropped to its low level.

14. Arditi, M. and T. R. Carver, "The Principles of the Double Resonance Method Applied to Gas Cell Frequency Standards." Proceedings of the IEEE, pp. 190–213, January 1963.

    In recent years, gas cell frequency standards, using optical pumping and optical detection of the 0–0 hyperfine transition in alkali metal vapors, have been developed with good performances regarding stability, reliability and ease of operation. In this paper the physical principles of the double resonance method used in this device are described. The factors affecting the accuracy of the gas cell frequency standard are discussed, together with the solutions adopted for optimum results. The possibility of developing an optically pumped rubidium master oscillator of very high spectrum purity at microwave frequencies is also briefly discussed.

15. Armour Research Foundation, Chicago, Ill., "Optically Pumped Materials Research," Interim Report No. 2, 1 October-31 December 1962. Noble, G. A. and S. Nudel man, Rpt. No. 219 10, 31 January 1963, Contract DA 009 ENG5173, AD–406 796L.

    Attempts to enhance the ability of phosphors to detect IR radiation by the simultaneous application of UV radiation (for pumping) and electric fields have been made on normally infrared quenching and stimulatible phosphors. Significant improvement in detectability was not accomplished. The preparation of samples, experimental procedure and results are described. The feasibility of a light amplifier using the Stokes shift to obtain the inverted population depends upon the lifetime of F centers. Equipment has been assembled for obtaining periodic, short time light pulses. It consists of a multisided spinning mirror system, and is described here with the shape of its output light pulses. A proposed light amplifier is examined to determine the effect of amplifier geometry on signal and noise. It is shown that the noise figure depends upon amplifier geometry as well as its material properties.

16. Army Electronics Research and Development Agency, Fort Monmouth, N.J., "On the Feasibility of an Ettingshausen Semi-Conductor Laser," Mette, H., E. Schiel and C. Loscoe, AELRDL TR2374, June 1963, AD–413 364.

    The possibility of achieving stimulated recombination radiation in a semiconductor by an alternate method to the injection diode is investigated. The results show that an excess concentration of recombination carriers sufficient to initiate laser action may be obtained in semiconductors by drift and deflection in a magnetic field (Ettingshausen effect). However, further data are required to calculate the exact size of the threshold value. Although the current densities required for operating the device appear of similar order as for injection diodes, the pumping method is based entirely on bulk effects. Therefore, the device offers a number of practical advantages over junction devices, such as a larger emitting area and fast response time. The design of a possible Ettingshausen laser is discussed in detail and problem areas for future work are listed.

17. Army Missile Command, Physical Sciences Lab., Redstone Arsenal, Ala., "Radiation Damage by Compton Scattering in Gamma or X-ray Pumped Optical Masers," Shates, R. A., Report RR-TN-63-2, 15 April 1963.

    The computation of threshold energies of X-rays and gamma rays for the displacement of a lattice element by the nuclear Compton scattering is reported. Numerical results are given for alkali halides and oxides. These computations were carried out as a part of a general feasibility study of direct pumping of optical masers by radiations emitted in the nuclear fission of transactinides. Based on the analysis of the fission data for U^{235}, it is concluded that the direct pumping is not yet technologically feasible because: (1) only a small fraction of the total energy released by the nuclear fission can presently be made available in X-rays and gammas, (2) serious radiation damage to the optical maser material would occur if fast neutrons or high-energy gammas were used in pumping. As an alternate, the conventional conversion of fission energy into electricity and the electrical pumping by carrier injection into recombination radiation devices is suggested.

18. Bell Telephone Labs., Inc., Murray Hill, N.J., "Fluorescence in CdS and its Possible use for Optical Maser," Thomas, D. G. and J. J. Hopfield, Journal of Applied Physics, Vol. 33, pp. 3243–3249, November 1962.

    Consideration of fluorescence from semiconductors for possible use in constructing a laser. Attention is given to the sharp-line emission which occurs at low temperatures in cadmium sulfide and which arises from excitons

bound to impurities. Some recent experimental results are summarized which give information concerning the fluorescent efficiency and the depth to which crystals are excited using UV light for excitation. Possible laser geometries are discussed, and the opportunities for using an evacuated ground state are pointed out. There appear to be several severe difficulties associated with the small depth of penetration of the exciting light, with the low fluorescent efficiencies available, and with the inability to grow large perfect crystals with controlled impurity content. With CdS, both phonon and Zeeman effects can be used to produce depopulation. The effects are briefly discussed. It is indicated that an improvement in the art of crystal growing is probably necessary before the effects described can be expected to result in a useful laser.

19. Bell Telephone Labs., Inc., Murray Hill, N.J., "The Laser," Yariv, A. and J. P. Gordon, Proceedings of the IEEE, Vol. 51, No. 1, pp. 4–29, January 1963.

    This article is intended as a review of the field of optical masers, or lasers as they have come to be known, summarizing both theory and practice. It starts with a theoretical section in black body radiation theory is used to introduce the concepts of spontaneous and induced transitions. This is followed by the derivation of the Schawlow Townes instability (start-oscillation) condition and a description of the different laser media. Other topics treated include: optical pumping, experimental techniques, output power and noise. The sections on optical resonators and communications which conclude the paper have been slightly emphasized since, perhaps to a larger extent than the other topics covered in this paper, they coincide with traditional areas of interest of microwave and communications engineers.

20. Bell Telephone Labs., Inc., Murray Hill, N.J., "CW Solid-State Optical Maser (Laser)," Quarterly Rept. No. 2, 15 October 1962–15 January 1963. Contract DA36 (039sc-89068, AD–405, 127.

    The further study of the diffraction-limited oscillator is presented. The variation of threshold pumping power, oscillator peak output power, and oscillator energy as a function of aperture size has been studied. Experimental studies of the spectral width of pulsed ruby oscillators are reported. The results of some of the measurements are consistent with the assumption of a homogeneous linewidth for ruby at room temperature and seem to indicate that spatial cross relaxation is not present in the ruby optical oscillator. Also reported are some experimental results which at present are not understood. The spectroscopic study of Yttrium Aluminum Garnet has continued. The spectrum of trivalent Eu in YtAl Garnet is discussed and a term scheme is suggested. Work during this last quarter has also continued on the TWOM. The 5-stage TWOM has been operated with a gain of 20 db and has produced output powers of 10 megawatts. This power output limitation was due to the driving oscillator and not the amplifier. A description of these experiments will be reported at a later date.

21. Bell Telephone Labs., Inc., Murray Hill, N.J., "The Focusing of Light by a Dielectric Rod," McKenna, J., Applied Optics, Vol. 2, pp. 303–310, March 1963.

    The focusing effect of a dielectric circular cylinder in a uniform, three-dimensional light field is studied. The cylinder consists of an absorbing core surrounded by a coaxial, nonabsorbing sheath. The dielectric constants of the core and the sheath are the same. An expression for the energy density (or the light intensity) in the core is obtained. The study was motivated by the problem of pumping a composite rod optical maser.

22. Bell Telephone Labs., Inc., Murray Hill, N.J., "Excitation Mechanisms and Current Dependence of Population Inversion in He-Ne Lasers," White, A. D. and E. I. Gordon, Applied Physics Letters, Vol. 3, pp. 197–199, 1 December 1963.

    Consideration of the results of spectral measurements of the spontaneous light intensity emitted from de-excited He-Ne gas laser tubes, as a function of discharge current. These measurements, in conjunction with measurements of the He metastable density, were used to explicate the role played by various discharge mechanisms in the creation of inverted populations in the He-Ne system. The spectral intensity measurements consisted in plotting on an x-y recorder the current and radial dependence of the Ne and He emission lines observed from the end and side of a short discharge tube, with a Jarrell-Ash ½-m Ebert Monochromator.

23. Belorussian Academy of Sciences. Physics Institute, Minsk, USSR, "Dependence of the Generation Thresholds of an Optical Generator on the Properties of the Cavity," Samson, A. M., B. I. Stepanov, and L. D. Khazov, Akademiia Nauk USSR, Doklady, Vol. 148, pp. 317–320, January 1963. Soviet Physics, Doklady, Vol. 8, pp. 54–56, July 1963 (A Translation).

    Determination of the threshold pumping energy for a three-level quantum generator. Among the results found is that for the threshold pumping power, the probability of a forced transition of particles to the third level is approximately equal to the probability of the departure of particles form the second level to the first level via the spontaneous and nonoptical effects.

24. Bloom, Arnold L., "Optical Pumping," Scientific American, Vol. 203, No. 4, pp. 72–80, 1 October 1960.

    In this new technique of experimental physics, light is used to "pump" electrons to higher energy levels. The method is employed to study the interaction of atoms and radio waves.

25. Bowness, C. and D. V. Missio, "Pulsed Solid State Lasers," Raytheon Electronic Prog., Vol. 7, pp. 2–6, January-February 1963.

    A review of the historical background of lasers and a description of some of the significant achievements in pulsed solid state lasers are presented. The MIT-Raytheon Moon Shot using a four-ellipse laser head with output energy of approximately 50 joules is described. The development of more powerful flash lamps and longer ruby crystals has lead to the 350 joule laser which when focused to a small spot is capable of boring through ⅛ inch thick steel in the millisecond or two that a single pulse lasts. The efficiency slightly exceeds 1 percent. Cooling the ruby to 77°K nearly doubles the efficiency of the device. Plans center around improvement of the efficiency of these high energy lasers. Four percent appears to be possible using ruby and the existing type of flash lamps. By using other dopants in place of chromium it is possible to achieve other frequencies than the characteristic 6943A ruby output. Some laser drawbacks including the phenomenon of random spiking are discussed. The possibilities of utilizing short pulse excitation techniques are suggested.

26. California Univ., Berkeley Electronics Research Lab., "Diatomic Gas Optical Maser with Exploding Wire Pumping Source," Hajdu, L., Report No. 63–12; AROD–33233, 5 June 1963. Grant DA–ARO (D)–31–124–G317, Contract AF 49(638)–102.

The feasibility of a gaseous maser in which the excited atoms are produced through photochemical decomposition of diatomic molecules (such as N_2, O_2, and NO) is studied. As an example, the photodissociation of NO is discussed in detail. Because of the required high excitation energies, the useful pumping band of such a system is in the extreme ultraviolet. Exploding wire is suggested as a suitable light source, having very intense output in the vacuum ultraviolet, with excellent reproducibility of its spectral characteristics per flash. Preliminary experiments show that when N_2 and O_2 molecules are photoactivated by the light output of an exploding wire, the 7468.8 A nitrogen and 8446 A oxygen emission lines appear with relatively high intensities.

27. California University, Dept. of Electrical Engineering, Berkeley, California, "Optical Masers," Singer, J. R., In Cyrogenic Technology, pp. 311–331, 1963, Vance, Robert W., ed.; John Wiley and Sons, Inc., New York.

Discussion of the optical or electronic excitation of gases and solids, and of the consequent coherent emission in the submillimeter, IR, or optical frequencies. Some ideas of Schawlow and Townes on general design principles of IR and optical coherent oscillators and amplifiers are reviewed. The problem of constructing a resonant structure with dimensions equal to one, or even a few, wavelengths, is considered, together with specific systems for obtaining inverted level populations. Also described is the possibility of obtaining negative absorption (amplification) by examining the relative populations of the upper- and lower-level states of atomic hydrogen in a Wood's electrical discharge tube.

28. Carnegie Institute of Technology, Pittsburgh, Pa., "Plasma Pinch Excitation of a Ruby Laser," Brandewie, Richard A., Joe S. Hitt, and J. M. Feldman, Journal of Applied Physics, Vol. 34, pp. 3415–3416, November 1963.

Brief description of ruby laser excitation with a high-current theta pinch in argon. An unusually intense and well-defined output pulse is obtained from the ruby with apparently negligible heating of ruby or flash tube. The pump light is found to consist of line spectra, rather than the blackbody continuum emitted by the xenon flash tubes ordinarily employed for laser excitation.

28. Church, Charles H., Walter K. Smith and Gene R. Feaster, "The Design and Development of the Laser Machine Tool," ASTME Creative Manufacturing Seminars, Tech. Paper SP 63–35, November 1962.

30. Cornetto, Alan, "Novel Pumping Schemes Studied to Boost Laser Power," Electronic Design, Vol. 10, No. 8, pp. 16–22, 12 April 1962.

31. Cornetto, Alan, "Table of Laser Frequencies," Microwaves, Vol. 3, pp. 45–49, January 1964.

The rapid growth of laser technology has led to generation of nearly 200 coherent optical and infrared frequencies in dozens of solids, liquids, and gases. The progress achieved in less than four years is dramatically evident in this up-to-date table.

32. Dacey, G. C., "Optical Masers in Science and Technology," Science, Vol. 135, No. 3498, pp. 71–74, 12 January 1962.

33. David Sarnoff Research Center, Princeton, N.J., "A Research Program on the Utilization of Coherent Light," Interim Rept. No. 6, 1 October 1962–31 December 1962. Blattner, D. J., G. Goldsmith et al., AD–296 145, 20 January 1963, Contract AF 33(616)8199.

A CaF2:Dy2+ optical maser, a cuprous-chloride electro-optic modulator, and a lead-selenide detector were used together in a demonstration of an optical maser communications system carrying an audio channel. The modulator is intriniscally capable of much larger bandwidth, and it is hoped that the system can be extended to a video channel by replacing the detector with a faster device. An optical maser has been operated in a pulsed mode at a high repetition rate suitable for tracking radar applications. The device, a CaF2:Dy+ maser, produced 90 pulses per second of infrared radiation at 2.36 microns. The high pulse repetititon rate was achieved by using a double-pumping technique. A continuously operating tungsten lamp was operated at a power level just below the threshold of operation of the optical maser. A pulsed xenon lamp was used as an auxiliary source to raise the pumping level above threshold for very short periods. A CaF2:Tm2+ maser was operated continuously for the first time this quarter. The device is of interest because it can be tuned over a large band of frequencies by application of a magnetic field. A GaAs p-n junction master has been operated at liquid nitrogen and helium temperatures.

34. Electro-Optical Systems, Inc., Pasadena, Calif., "Research and Investigation of Materials for Laser Applications," Final Rept. 30 April 1962–30 June 1963, Lee, S. M. and K. A. Yamakawa, Rept. ASD TDR63 603, May 1963. AD–412 863, Contract AF33 657 8918, Project 4460, Task 446002.

This report describes the results of a study for the preparation and characterization of optimized solid state materials for laser applications. Primary emphasis was placed on the rare-earth organic chelates, but also included the development of special glasses as host materials for rare-earth ions. The rare-earth ions and ligands studied were: Eu+ 3, Nd+ 3, Er+ 3, Tb+ 3, Sm+ 3, and Pr+ 3 in conjunction with the ligands of acetylacetone, trifluoroacetylacetone, thenoyl trifluoroacetone, ethylacetoacetate, dibenzoylmethane, bensoylacetone, phthalocyanine, and prophyrin. Moderate to high intensity fluorescence emission was observed for the chelates of europium, terbium, and samarium. Halogenation was found to improve the fluorescence emission. A host material study including molecular organic crystals, plastics, and organic liquids was made. A glass host material having a high fluorescence efficiency when doped with neodymium ions was developed. Glass matrices capable of being pumped both in the visible and ultraviolet when doped with neodymium ions were also developed.

35. Electro-Optical Systems, Inc., Pasadena, California, "High Intensity Pump for Optical Lasers," Final Report, 1 July 1962–1 April 1963, Clark, G. L., N. C. Chase and H. R. Moore, Report No. 3270, August 1963, Contract AF33 657 8805, AD–416, 024.

The development, construction, and testing of a laser head in which the source of pump radiation is the dense hot plasma produced by electrically exploded wires is described. A capacitor bank energy storage system was constructed which has a maximum capability of 150,000 Joules at 20 KV. It consists of nine independent sections which can be operated in any parallel combination. The capacitor sections are switched with ignitrons, the measured ringing frequency being 50 KC/sec with a rise time of 5 x 10⁻" seconds. Utilizing one section of the energy storage system, the radiation characteristics of electrically exploded tungsten wires were evaluated over the wavelength range 2500–8500 Angstroms using a plane grating spectograph. The peak spectral radiance of exploding tungsten wires was measured at 5460 Angstroms using an absolutely calibrated photomultiplier detector and narrow band filter combination. The problem of efficiently transferring the radiation from an exploding light source into a laser rod was considered. Some conclusions were drawn with regard to the optical aspects of this problem sufficient to allow the design and construction of a multiple exploding wire laser head. The multiple exploding wire laser head. The multiple exploding wire laser head, the energy storage system, and the control system have satisfactorily undergone electrical tests.

36. Electro-Optical Systems, Inc., Pasadena, Calif., "Optically Pumped Image Light Amplification," Quarterly Report No. 1, 10 May 63–10 August 63, Bernstein, H., P. Fletcher, B. Kazan, L. Nugent, and D. Weisman, Rept. No. 3390Q1, August 1963, AD–415 361, Contract AF33 657 11326, Project 4156 05.

Primary attention has been given to the problem of the generation of background light caused by spontaneous emission and its amplification in passing through an intensifier. Because of the high fluorescence level occuring, schemes for possibly lowering this background were considered. One of these involves the incorporation of a non-uniform pumping intensity or the incorporation of a non-uniform density of luminescent states along the amplifier axis. Another possibility considered is the use of an auxiliary absorbing medium placed between the intensifier output and the observer's eye, which would be optically non-linear in such a way that its light transmission is low below a specified light level, but high above this threshold. The factors concerned with the choice of a material for the amplifier itself were separately considered, and the problem of obtaining uniform pumping in the case of an optically-pumped amplifier was also considered.

37. Garrett, C. G. B., "The Optical Maser," Elec. Engr., Vol. 80, No. 4, pp. 248–251, April 1961.

A brief description is presented of a solid-state device, a ruby maser, that utilizes the principles of microwave amplification by stimulated emission of radiation (maser). Experiments under way point to a new medium of communication in which a be·m of light is used to transmit vast amounts of information from one point to another.

38. General Dynamics Corp., Physics and Infrared Section, Pomona, Calif., "UV Exciton Laser," Fink, E. L. and G. N. Ellison, Proceedings of IEEE, Vol. 51, p. 951, June 1963.

Investigation of the theoretical possibility of stimulating UV laser oscillation from exciton levels in pure KI. It is indicated that the relatively broad emission band of KI (800 A) suggests that it could be used as a coherent (spatially) broad-band amplifier when pumped below the oscillation threshold. In order to obtain highly monochromatic emission form KI, the crystal would have to be pumped well above threshold. The emitted energy would be distributed among many cavity modes, each with its frequency pulled toward the center of the exciton band.

39. General Electric Co., "Semiconductor Laser," Research Laboratory Bulletin, pp. 16–17, Summer 1963.

Discussion of a novel type of laser in which coherent light is generated directly by passing an electric current through a semiconductor crystal. The device does not require pumping by an auxiliary process; instead, the excitation is achieved directly by injecting electrons (and holes) into the plane of the junction region (a plane less than 0.001 in. thick) in the middle of a tiny diode of gallium arsenide. The directional and coherent beam of IR light, with a wavelength of the order of 8400 A, is emitted from the junction-plane edges at two carefully polished and precisely parallel sides of the device.

40. General Electric Co., Electronics Lab., Syracuse, N.Y., "Optical Pumping of Microwave Masers," Hsu, H. and F. K. Tittel, Proceedings of IEEE, Vol. 51, pp. 185–189, January 1963, Contract No. DA–36–039–sc–87209.

Discussion of the application of optical pumping techniques to microwave masers. It is shown that optical pumping appears to be promising for achieving low-noise maser action at very high frequencies and at elevated temperatures. The analysis includes the treatment of optical-pumping principles, noise considerations, pump-power requirements, and maximum signal frequencies. Potential advantages and limitations which can exist when using optical excitation are considered. The developed concepts and procedures are applied for illustrative purposes to evaluate the expected performance of a ruby maser.

41. General Electric Co., General Engineering Lab., Schenectady, N.Y., "Focused Side Pumping of Laser Crystal," Tomiyasu, K., Proceedings of IRE, Vol. 50, pp. 2488–2489, December 1962.

Study of the focused side pumping of laser crystal as found, for example, in an elliptic configuration. In this simplified analysis it is assumed that all the pump flux-propagation vectors are normal to the laser rod axis, and that the flux is constant and independent of direction of arrival. It is shown that at low energy levels, focusing in the laser rod is enhanced since the flash-lamp discharge diameter is smaller than at higher energy levels. A diagram showing the pump flux distribution inside a laser crystal is presented.

42. General Electric Co., Heavy Military Electronics Dept., Syracuse, N.Y., "Pulse Power Supply Design for Laser Pumping," Grabowski, S. J., Electronics, Vol. 36, pp. 33–35, 20 December 1963.

Practical circuit design that specifies a minimum of equipment combines constant-current capacitor charging with limiting of output voltage.

43. General Electric Co., Research Lab., Schenectady, N.Y., "The Laser," Kingsley, J. D., Rept. No. 63–RL–3306–G, April 1963.

An elementary, qualitative discussion of the laser is given, including a description of stimulated emission. Several fundamental means of achieving a population inversion are discussed as well as the basic form of a laser. The areas in which lasers may be applied are discussed briefly and in very general terms.

44. General Telephone and Electronics Labs., Inc., "A Solution for Continuous Pumping of Solid-State Lasers," Keck, Paul H., Bulletin American Physical Society, Vol. 7, No. 1, Pt. 1, p. 15, 24 June 1962, Paper CA9 presented at the 1962 Annual Meeting at New York, 24 January 1962–27 January 1962.

It will be shown that a continuous luminous flux which is above the threshold value required for pumping solid-state laser materials, such as ruby, can be obtained using a xenon arc lamp or the sun as the light source. A suitable optical system for continuous pumping, including a proper geometry of the laser crystals, will be described. This system allows filtering of the pumping flux, as well as cooling of the crystal in a convenient way, since light source and laser crystal are not arranged in close proximity.

45. General Telephone and Electronics Labs., Inc., "Pumping Requirements for CW Solid-State Lasers," Keck, Paul H., Bulletin American Physical Society, Vol. 7, No. 2, p. 118, 23 February 1962, Paper presented at 1962 Southwestern Meeting of The University of Texas, Austin, 23 February 1962–24 February 1962.

The conditions for continuous pumping of a solid-state laser material, depending on the spectral distribution of the source, absorption characteristics, threshold for laser action, and geometry will be discussed. Several suggested arrangements for CW solid-state lasers will be described.

46. General Telephone and Electronics Labs., Inc., Bayside, N.Y., "Power and Efficiency Consideration in Continuous Laser Operation," Appendix—Steady-State Equations for 4-Level Laser," Frankl, D. R., Journal of Applied Physics, Vol. 34, pp. 459–462, March 1963.

Summary of various factors entering into the continuous operation of optically pumped solid-state lasers. Numerical estimates for ruby and for Nd^{+++}-activated materials in two types of optical systems suggest that several watts of output power should, ideally, be obtainable when pumping with a 1-kw Hg arc lamp.

47. General Telephone and Electronics Labs., Inc., Bayside, N.Y. Argonne National Lab., Argonne, Ill., "A Method for Determining the Threshold of Laser Materials," Lempicki, A. and R. L. Martin, Proceedings of IEEE, Vol. 51, pp. 1778–1779, December 1963.

Demonstration that a single measurement of absolute emission intensity at the peak of a fluorescent line of a material determines, in principle, the flash energy necessary to cause laser oscillation. No detailed knowledge of absorption and quantum efficiency is necessary. It is shown that, since this applies to ruby as well as any other material, and the threshold excitation of ruby is known, a comparison of the relative emission intensity of the material to that of the R_1 line of ruby also yields the desired result.

48. General Telephone and Electronics Labs., Inc., Palo Alto, Calif., "Fluorescence and Stimulated Emission from Trivalent Europium in Yttrium Oxide," Chang, N. C., Journal of Applied Physics, Vol. 34, pp. 3500–3504, December 1963.

Description of measurements of the absorption, emission, and excitation spectra of Eu^{3+} in Y_2O_3, and also of fluorescence lifetime and quantum efficiency. An approximate level scheme is given. Conditions for laser action are calculated, and the results of a laser experiment are described. The importance of a strong UV excitation band probably corresponding to transitions from f-electrons to d-electron levels is indicated.

49. Goodwin, Deryek, "Lasers—Fact and Fiction," Discovery, Vol. 15, No. 4, pp. 26–30, April 1964.

One of the most exciting technological discoveries of the decade, the laser has been hailed as the new "death ray" and a final answer to communications problems. But after four years of research its uses are still confined to the laboratory. What are the real facts behind the laser's future?

50. Harris, Aubrey, "Lasers I," Wireless World, Vol. 69, pp. 370–375, August 1963.

General description of the basic operating principles and characteristics of different classes of lasers. Those discussed are doped-crystal, gas-discharge, semiconductor-junction, and liquid. A table lists their operating characteristics, including output frequency, spectral width, beamwidth, pumping requirements, and efficiencies. The active materials and output wavelengths of various types of lasers are also tabulated.

51. Hewlett-Packard Co., Palo Alto, Calif., "Some Potentialities of Optical Masers," Oliver, B. M., Proceedings of IRE, Vol. 51, pp. 135–141, February 1962.

This paper, originally presented at the 1961 WESCON Convention, is intended as an introduction to the principles and possible applications of the optical maser. Very little prior knowledge on the part of the reader is assumed. The intent is to acquaint him with these exciting new devices with the hope that he, in turn, will discover applications not foreseen by the author. The methods of generating coherent radiation, of focussing it, and of collimating it into tight beams are described. The use of lasers for communication is explored, and certain medical and other applications are suggested.

52. Honeywell Research Center, Hopkins, Minn., "An Analysis of Radiation Transfer by Means of Elliptical Cylinder Reflectors," Schuldt, S. B. and R. L. Aagard, Applied Optics, Vol. 2, pp. 509–513, May 1963.

Derivation of expressions which give the relative amount of pumping radiation transferred from a cylindrical source to a cylindrical laser by means of a reflector in the shape of an elliptical cylinder. The general expression depends upon the radii of the source and laser, the eccentricity of the ellipse and the length of its semimajor axis, and an arbitrary angular distribution of source radiation. The effect of radiation reflected back into the source itself (source-blocking) is also considered. A considerable simplification in the calculation results when the source distribution is invariant under a rotation of the source about its axis, i.e., when the distribution depends only on the direction of the radiation with respect to the local normal, thus corresponding to virtually all practical cases. Moreover, the special case of a Lambertian source distribution yields efficiencies which may be evaluated directly. Especially simple and illustrative is the Lambertian source which is sufficiently small compared with the reflector so that source-blocking can be ignored.

53. Howell, B. J. and W. M. Macek, "Lasers," Discovery, Vol. 13, No. 9, pp. 16–22, September 1962.

The production of a pure and coherent form of light has been hailed as the most important technical innovation of the last three years. Opening up a completely new range of optical science, the laser is finding applications in fields as far apart as space communication and microsurgery.

54. Hughes Aircraft Co., Culver City, Calif., "Laser Applications," Stitch, M. L., Solid/State/Design, Vol. 4, No. 11, pp. 33–37, November 1963.

55. Hughes Aircraft Co., Research Labs., Malibu, Calif., "Laser-Generation of Light by Stimulated Emission," Lengyel, Bela A., John Wiley and Sons, Inc., New York 1963.

Review of the laser state-of-the-art and its present level of achievement. The book, a reference source for both student- and graduate-level scientists, emphasizes principle rather than engineering design, and includes background material on light and radiation. Described are: (1) Maiman's ruby laser, (2) Javan's gas laser, (3) solid- and liquid-state lasers, (4) analytical problems, and (5) applications and development. Current development problems are explored, and information published after completion of the text is reported in a supplement.

56. Hughes Aircraft Co., Research Labs., Malibu, Calif., "Extension of the Laser-Pumped Ruby Maser to Millimeter Wavelengths," Devor, D. P., Institute of Electrical Engineers, Millimeter and Submillimeter Conference, Orlando, Fla., 7 January 1963–10 January 1963, IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-11, pp. 251–254, July 1963.

Brief description of the operation of a microwave ruby maser in which the pump signal is the optical emission of a ruby laser. It is shown that, for operation in the millimeter spectrum, the application of a magnetic field of inordinately high intensity can produce Zeeman splitting of the Cr^{3+} levels at millimeter wave energy in the ground state in ruby. To obtain population inversion by optical pumping on the levels requires that the ratio of maser frequency to temperature be $\nu_{ij}/T < 14.4$ Gc/sec. °K. A broadening of the laser emission has been observed at increased power so that the limit on useful laser power can be given in terms of the absorption-line width of the maser optical pumping transition. Treating these various effects conservatively indicates that the laser-pumped ruby maser can be operated over the entire millimeter spectrum. The design of an apparatus with a hard superconductor electromagnet producing the field intensity required to accomplish this objective is given.

57. International Business Machines Corp., Federal Systems Div., Bethesda, Md., "Injection-Laser Systems for Communications and Tracking," Johnson, C. M., Electronics, Vol. 36, pp. 34–39, 13 December 1963.

Injection lasers can now be applied advantageously in some communications problems and may well be the system of choice for space missions. Possibilities for high precision radar tracking are also excellent but more work is needed in this area.

58. International Business Machines Corp., Thomas J. Watson Research Center, Yorktown Heights, N.Y., "Spectral Characteristics of Exploding Wires for Optical Maser Excitation," Stevenson, M. J., W. Reuter, N. Braslau, P. P. Sorokin, and A. J. Landon, Journal of Applied Physics, Vol. 34, pp. 500–509, March 1963, Army-supported research.

Experimental investigation of the light output for relatively slow wire explosions in air and in evacuated quartz tubes. As pulsed light sources, exploding wires can be used to provide intense narrow spectral lines as well as the characteristic continuum of very high temperature blackbodies. The surface brightness depends on the wire material and the conditions under which the wire is exploded. Optimum conditions for 100–150μ sec long light pulses from wires exploded in air are found for tungsten, tantalum, and molybdenum wires (0.005–0.010 in. diam.) for energy inputs of 3,000 joules or more. Wires exploded in small-diameter vacuum tubes (1–20μHg) radiate as blackbodies, but narrow-line spectra are produced in enclosures of larger dimensions. In the visible and UV regions of the spectrum, the spectral radiance of air-exploded wires is one to three orders-of-magnitude greater than that of conventional flash lamps. Vacuum-exploded wires have a spectral radiance that is greater by a factor of four to eight than air-exploded wires.

59. International Business Machines Corp., Thomas J. Watson Research Center, Yorktown Heights, N.Y., "Injection Lasers: State of the Art," Nathan, Marshall I. and Gerald Burns, Electronics, Vol. 36, pp. 61–65, 6 December 1963.

Description of the principles of operation and properties of a laser that skips the intermediate step of optical pumping and converts dc power directly into coherent light. The injection lasers are thus more efficient and compact, and offer attractive possibilities for internal modulation, so they should be useful in the communication field. Other advantages include power conversion efficiency, observed in excess of 50 percent and CW output power surpassing that of any other existing laser.

60. International Business Machines Corp., Yorkton Heights, N.Y., "Optically Pumped Solid State Materials," Sorokin, P. P. and W. V. Smith, Rept. RC-848; AROD-3318-9, 22 October 1962, Contract DA 30-069-ORD-3542, Available to U.S. Government Agencies only.

The theory of optical transitions of rare earth ions in crystals is discussed. Emphasis is placed on the spectra of $^{+2}$ ions in O_h symmetry. Among the topics discussed are 4f → 4f static-lattice transitions, 4f → 4f vibronic transitions, 4f → 5d vibronic transitions, and nonradiative transitions between both $4f^{n-1}$ 5d configurations.

61. Jadavpur University, Dept. of Telecommunication Engineering, Calcutta, India, "Laser and Coherent Optical Radiation," Deb, S., P. K. Chowdhury and M. K. Mukherjee, Journal of Scientific and Industrial Research, Vol. 22, pp. 314–334, August 1963.

Brief description of recent developments in the field of lasers. The basic principle of laser operation is outlined and a simple mathematical approach to the theory of laser indicated. The performance of various types of resonators used in the optical range is discussed. A classification of the different types of lasers developed so far is proposed, and representative experimental systems illustrating the various classes are described. The results obtained are also briefly reviewed. The significance of coherent optical emission is explained and the extent of coherence achieved so far with lasers is mentioned. The outstanding properties of coherent laser output are enumerated and the possible scientific and technological applications of these are described.

62. Kiss, Z. J., H. R. Lewis and R. C. Duncan, Jr., "Sun Pumped Continuous Optical Maser," Applied Physics Letters, Vol. 2, No. 5, pp. 93–94, 1 March 1963.

Optical maser action in CaF_2 $-Dy^{2+}$ crystal system at liquid neon temperature (27°K), using sun as pumping source; low pulsed maser threshold, long lifetime (10 msec for 0.05 molar % Dy^{2+} in CaF_2), and convenient location of broad pumping bands make it especially suitable for sun pumped operation in satellite where radiation cooling might be possible.

63. Korad Corporation, Santa Monica, Calif., "Optically-Pumped Solid State Lasers," Maiman, Theodore H., Solid/State/Design, Vol. 4, No. 11, pp. 17–21, November 1963.

64. Kroeger, Robert D., "Pulsed Optical Laser Radar," Sperry Engineering Review, Vol. 15, pp. 44–53, Winter 1962.

Description of a pulsed laser radar, and presentation of several examples that demonstrate the radar's range and angular resolution capabilities for observations made near the horizon in daylight. Two versions of Q-switched lasers are described. Concepts of two systems are discussed. In one, the target is measured by electronic scanning; and in the other, the target is illuminated and imaged using the laser's high-power density. Both depend upon the laser's narrow-beam capability. To demonstrate the capability of the radar, a typical ranging system is analyzed, in which, with the radar located on the ground, the SNR is computed for nighttime ranging on an Echo-type satellite 1,000 miles away.

65. Levine, Albert K., "Lasers," American Scientist, Vol. 51, pp. 14–31, March, 1963.

66. Li, Tingye and S. D. Sims, "Observations on the Pump-Light Intensity Distribution of a Ruby Optical Maser with Different Pumping Schemes," Proc. Inst. Radio Engrs., Vol. 50, pp. 464–465, April 1962.

67. Luck, C. F., Jr., "Experimental CW Solid State Lasers," Raytheon Electronic Prog., col. 7, pp. 12–16, January/February 1963.

The state-of-the-art of CW solid state lasers is reviewed. Problems entering in design considerations are: required pumping energy intensity to preserve the necessary inverted population, heat dissipation due to laser inefficiency, second order effects due to temperature differences in the crystal which tend to limit performance, and crystal quality. Details of the required optical resonator geometry are given. The optimum resonator configuration is confocal with a cross-section and length chosen to match the lamp with the highest brightness and the most suitable spectral distribution obtainable. Results obtained with neodymium-doped and dysprosium-doped calcium fluoride CW lasers are outlined.

The possibility of utilizing the sun as a source of pumping radiation for space laser application is suggested. Some recent Raytheon CW laser experiments are also briefly described.

68. Martin Company, Orlando, Fla., "The Maser," Brinley, B. R., The Microwave Journal, Vol. 5, No. 8, pp. 86–94, August 1962.

69. Massachusetts Institute of Technology, Cambridge, Mass., "Gaseous Optical Masers," Javan, A., Solid State Design, Vol. 4, No. 11, pp. 22–25, November 1963.

70. Massachusetts Institute of Technology, Cambridge, Mass., "Semiconductor Diode Lasers," Lax, Benjamin, Solid/State/Design, Vol. 4, No. 11, pp. 26–32, November 1963.

71. Massachusetts Institute of Technology, Lincoln Lab., Lexington. Mass., 'Criterion for Continuous Amplitude Oscillations of Optical Masers," Kaplan, Jerome I., Journal of Applied Physics, Vol. 34, pp. 3411–3412, November 1963.

Demonstration that a long-time solution having a time-varying amplitude can be obtained for a previously derived set of equations describing a three-level laser self-oscillating between the upper two levels. No attempt is made to find the particular analytic form of the solution. It is noted that the previously derived minimum condition for the pump power is much greater than that attained by Bostick and O'Connor, so that no continuous amplitude oscillation for the latter's $CaF_2:U^{+3}$ laser system should be expected.

72. Michigan University, Institute of Science and Tech., Ann Arbor, Mich., "Effects of γ-Irradiation on the Performance of a Ruby Laser," Flowers, W. and J. Jenney, Proceedings of IEEE, Vol. 51, pp. 858–859, May 1963, Contract No. DA-36-039-78801.

Description of experiments showing that irradiation of ruby-laser rods with Co^{60} gamma rays substantially increases their efficiency. The increase in efficiency is seen to be caused by a more efficient absorption of the pump light by color centers produced in the ruby by irradiation. However, the mechanism of energy transfer between the color centers and the laser transition is not yet determined.

73. Mikaelian, A. L. and Iu. G. Turkov, "Kogerentnye Generatory Opticheskogo Diapazona," (Coherent Generators of Optic Range), Radiotekhnika i Elektronika, Vol. 8, pp. 731–758, May 1963 (in Russian).

Review of the present state of research activities in the field of lasers. The principles of operation of both solid-state and gaseous lasers are considered. Different designs of lasers are described and their parameters given.

74. Miles, P. A. and H. E. Edgerton, "Optically Efficient Ruby Laser Pump," Journal of Applied Physics, Vol. 32, No. 4, pp. 740–741, April 1961.

75. Moscow State University, USSR, "The Effect of Cross Relaxation on Population Inversion in Ruby," Klyshko, D. N., V. S. Tumanov and L. A. Ushakova, Zhurnal Eksperimental' noi i Teoreticheskoi Fiziki, Vol. 43, pp. 25–30, July 1962. Soviet Physics—JETP, Vol. 16, pp. 17–20, January 1963 (a Translation).

Experimental investigation of the inversion of spin-level populations induced by a pumping signal in ruby (Al_2O_3 with an admixture of Cr^{3+} ions) for various values of θ, the angle between the crystal symmetry axis and the direction of the external magnetic field. The investigation is performed at a frequency of 3,000 Mc; the pumping signal varies between 9 and 17 Gc. The observations are made at 4.2° and 1.8°K. Crystals with Cr^{3+} concentrations of 0.001, 0.01, 0.02, 0.35, and 0.12 percent are studied. The extrema found in the angular dependence of inversion are explained by cross-relaxation effects. It is pointed out that it should be possible to design a paramagnetic amplifier having a signal frequency higher than the pumping frequency by using two substances with two paramagnetic admixtures.

76. Moscow State University, Nuclear Physics Inst., Moscow, USSR, "The Generation of Millimeter Waves in Ruby by Optical Pumping," Zverev, G. M., A. M. Prokhorov and A. K. Shevchenko, Zhurnal Eksperimental' noi i Teoreticheskoi Fiziki, Vol. 44, pp. 1415–1418, April 1963, Soviet Physics—JETP, Vol. 17, pp. 952–954, October 1963 (a Translation).

Experimental investigation on the generation of millimeter wavelength radiation in the range 35–50 x 10^9 cps, using ruby cooled to liquid nitrogen temperature. The experimental arrangement is described and schematically diagramed. The microwave radiation is found to appear in "spikes" on the oscilloscope screen. The frequency of the spikes increases when the energy of the laser pulse increases. The principal features of the operation of a quantum paramagnetic amplifier with optical pumping are briefly described in terms of an analysis of the kinetic equations for a system of three energy levels, taking into account the large energy interval between the two lower and the third upper levels.

77. National Bureau of Standards, Washington, D.C., "Dependence of Power Output of a Gas Laser on the Length and Rate of Excitation of the Discharge, White, J. A., Applied Physics Letters, Vol. 3, pp. 107–109, 1 October 1963.

Analytic investigation of the characteristic features of the gas laser output to be expected when the frequencies of oscillation are sufficiently far apart that interactions between the different modes can be neglected. It is assumed that the resonant frequencies of these modes are all displaced from the atomic frequency by at least a natural atomic linewidth, so that only those atoms moving fast enough along the axis of the cavity for there to be a Doppler shift of this magnitude will interact appreciably with the radiation. It is shown that the number of photons in an isolated mode increases high above threshold as the square of the rate of excitation. The results are compared to those of White, Gordon, and Rigden.

78. National Physical Laboratory, Light Division, Teddington, Middlesex, England, "Optical Research and the Solid State Laser," Burch, J. M., Institute of Physics and Physical Society, Annual Exhibition, London, England, 15 January 1963, Journal of Scientific Instruments, Vol. 40, pp. 147–152, April 1963.

Review of recent progress in laser research. Emphasis is on the following areas: (1) examination of materials, both gaseous and solid, which have been used as the fluorescent devices and the improvements made on these materials; (2) application of lasers to communications and optical experiments; (3) theoretical considerations and comparisons of lasers with other light sources; and (4) factors which intervene to prevent the ideal single-mode type output of laser oscillators.

79. National Research Council, Radio and Electrical Engr. Div., Ottawa, Canada, "Microwave Maser Action in Ruby at 78°K by Laser Pumping," Szabo, A., Paper presented at the Symposium on Optical Masers, Polytechnic Institute of Brookyln, April 16–19, 1963.

Maser amplification and oscillation at X-band have been observed at 78°K in ruby, using a ruby laser as a pump. The laser frequencies were matched to the required optical transitions in the microwave ruby by thermal tuning of the latter ruby. Measurements of the thermal tuning rate of the R_1 line in ruby using the paramagnetic resonance absorption of the ground state levels for direction will be described, as well as the conditions under which microwave maser action was obtained.

80. Nielsen, J. W., "The Improvement of Light Pumped Optical Maser Crystals," Proceedings of IEEE Nat. Aerospace Electronics Conference, pp. 276–281, 1963.

81. North American Aviation, Inc., Space and Information Systems Div., Downey, Calif., "Space Communications by the Use of Lasers; An Enumerative Bibliography," Simmons, Paul L., IRE Transactions on Communications Systems, Vol. CS–10, pp. 449–456, December 1962.

This paper traces the history of lasers in relation to communication and other applications from their inception to early 1962. Documentation includes books and periodicals including foreign language research.

82. North American Aviation, Inc., Space and Information Systems Div., Information Systems Lab., Torrance, Calif., "Efficiency of a Multiple Elipses Confocal Laser Pumping Configuration," Fried, D. L., and P. Eltgroth, Proceedings of IRE, Vol. 50, p. 2489, December 1962.

Presentation of the results of a study of an optical pumping system which uses several light sources and several truncated elliptical cylinders. It is shown that the expected improvement in ability to concentrate large amounts of light at the absorber is nonexistent. It is found that, while large eccentricity in the ellipse increases the angle over which light would be gathered and focused in each of the truncated ellipses, it has the advantage of increasing the spread of the image. In order to demonstrate the significance of the eccentricity the relationships are tabulated between the semimajor axis, semiminor axis, the eccentricity, and the percentage of the light gathered when the ellipse is so truncated as to allow four light sources to pump one laser rod.

83. Oxford University, Oriel College, Clarendon Laboratory, Oxford, England, British Institution of Radio Engineers, Symposium on Masers and Lasers, London, England, 2 January 1963, Journal of British Institution of Radio Engineers, Vol. 24, pp. 365–372, November 1962.

Review of optical masers, with emphasis on the principle of the maser and its extension to the IR and visible region of the spectrum. Various types of optical maser which have been successfully operated are described. The unique features of high spectral purity and narrow beamwidth are pointed out, and some present and future applications are considered.

84. Philco Corp., Western Development Labs., Palo Alto, Calif., "Semiclassical Treatment of the Optical Maser," Davis, L. W., Proceedings of the IEEE, Vol. 51 No. 1, pp. 76–80, January 1963.

Using the semiclassical theory of radiation, the steady-state operation of the optical maser oscillator is studied in the case where a single "cavity" mode is excited. On introducing certain simplifying assumptions, a straightforward calculation leads to concise results for the frequency and amplitude of the field oscillations. These results are either well-known or readily interpreted. For example, a frequency pulling effect is predicted which corresponds to the Bloch-Siegert shift, or alternatively is understandable as due to the Stark effect.

85. Picatinny Arsenal, Dover, N. J., "An Investigation into the Feasibility of a Pyrotechnic Laser Pump," Smith, Chester L. and Paul J. Kisatsky, Rept. No. PA-TR-3102, August 1963.

Pyrotechnic compositions consisting of two basic ingredients, fuels and oxidizers, were tested in various combinations. Combinations of pyrotechnic ingredients and high explosives were also examined, and high explosives in various configurations were tested. Brightness tests on the above combinations were conducted with various means of containing and confining the materials. A squib of $Zr/KClO_4$ emerged as the brightest emitter. The brightness was enhanced by use of a particular fixture. (This laser pump fixture utilized distributed pyrotechnics on the printed-bridge wire matrix.) The ingredients of the $Zr/KClO_4$ were varied from stoichiometric to a fuel-rich combination with the stoichiometric ratio giving the highest output on the brightness bench. The temperature reached with the combination was 4900°K. The brisance of the explosive and pyrotechnic composition was high and would therefore pose a severe problem when trying to avoid damage of the laser crystal. Consequently, it has been decided to work with a pyrotechnic composition, $Zr/KClO_4$ in particular, in a standard squib body rather than with an explosive and pyrotechnic composition.

86. Princeton University, Palmer Physical Laboratory, Princeton, N. J., "Optical Pumping," Carver, Thomas R., Science, Vol. 141, pp. 599–608, 16 August 1963.

Discussion of the process of redistribution of atoms among their fine- or hyperfine-structure levels by means of light. The selection rules of ordinary dipole radiation are reviewed, and the effects of circularly-polarized light on atoms are described. Methods of detecting optical pumping, and conversely, of using the pumping process as a detector in RF and microwave spectroscopy, are discussed. Considered is a method involving irradiation of the sample with light of a frequency which corresponds to that of one of the possible fine or hyperfine transitions of the atom in the magnetic field. The spin-exchange process and the application of pumping to atoms in metastable states are also discussed.

87. Rabinowitz, P., S. Jacobs and G. Gould, "Continuous Optically Pumped Cs Laser," Applied Optics, Vol. 1, pp. 513–516, 1962.

A continuously operating 7.18-μ laser oscillator has been built using optically pumped cesium vapor as the amplifying medium. A power of 50 μW is coupled out of the confocal resonator by means of a 45° BaF_2 pickoff window. The measured intensity distribution is in good agreement with that derived from the Boyd-Gordon expression for the lowest-order mode.

88. Radiation, Inc., Stanford Div., Palo Alto, Calif., "Variation of Arc Resistance and Arc Power with Current in Pulsed Xenon Optical Pump Lamps," Heard, H. G., Proceedings of IEEE, Vol. 51, pp. 1234–1235, September 1963.

Analysis of extensive measurements on linear, helical, and concentric flash lamps, indicating the current-dependent character of arc resistance. The effects of discharge circuit parameter variation upon arc impedance are included. Results are reported for a 4-in. arc-length straight lamp of 3-mm bore. Despite the extremely nonlinear character of arc resistance, it appears that the greatest efficiency may be obtained from laser optical pump lamps when they are excited by essentially square pulses.

89. Radio Corporation of America, Camden, N. J., "Development of Effective Lasers," Murray, L. A., M. F. Lamorte and F. L. Vogel, Radio Corp. of America, Somerville, N. J. Lasers, pp. 8–11, 1963.

Effort has been devoted toward minimizing strain and impurities in grown laser crystals. Described are the effects on laser performance of the polish, parrallelism, and reflecting surfaces of the prepared laser rod and the geometry of the pumping system, as well as the construction of absolute and relative threshold measurement apparatus.

90. Radio Corporation of America, Camden, N. J., "Q-Switched $CaWO_4$: Nd^{3+} Laser," Karlsons, D. and T. Falvey, Journal of Applied Physics, Vol. 34, p. 3407, November 1963, Contract No. AF 30(602)-2761.

Brief description of the successful Q-switching of a $CaWO_4$:Nd^{3+} laser operated at room temperature, with an output consisting of a variable number of short pulses (including the case of a single pulse), the number depending on the reflector separation. The crystal, ¼-in. in diameter and 2 in. long, was pumped in an elliptical reflector. Q-switching was effected by means of a porro prism rotating at 24,000 rpm. The crystal end facing the prism was uncoated; the opposite end, through which the output was monitored, was coated with dielectric layers having a nominal 99 percent reflectivity at 1.06μ. The Q-switched laser output is discussed.

91. Radio Corporation of America, Princeton, N. J., "A New GaAs Laser that can be Pumped Electrically," Pankove, J. I., In RCA, Camden, N. J. Lasers, p. 28, 1963.

A very simple, electrically pumped, semiconductor laser was developed, that is comprised of a p-n junction diode in a wafer of gallium arsenide. The gallium arsenide was converted into a laser by altering its shape, by decreasing the contact resistance to reduce losses, and by increasing the current density through the junction.

92. Radio Corporation of America, Princeton, N. J., "Sun-Pumped Continuous Laser," Duncan, R. C., Jr., Z. J. Kiss, and H. R. Lewis, In RCA, Camden, N. J., Lasers, p. 27, 1963, 04–25, Contract AF 33(616)-8199.

Laser action has been achieved in a CaF_2:Dy^{2+} system at liquid-neon temperature (27°K) using the sun as the pumping source. This laser action in the CaF:Dy^{2+} system was reported at 2.36 microns. The low pulsed laser threshold, the long lifetime, and the convenient location of the broad pumping bands of this system make it especially suitable for sun-pumped operation.

93. Raytheon Co., Research Div., Waltham, Mass., "Zeeman Effects in Gaseous He-Ne Optical Masers," Paananen, R., C. L. Tang, and H. Staz, Proceedings of IEEE, Vol. 51, pp. 63–39, January 1963.

Experimental and theoretical study of the Zeeman effects in a gaseous He-Ne laser under weak and normal excitation conductions. Attention is confined to the strongest maser emission line ($2s_2 \rightarrow 2p_4$). Under weak excitation conditions, the maser emission is a doublet of right and left circularly polarized waves. These may belong either to the same cavity mode or to different cavity modes, depending on the strength of the applied magnetic field. When viewed through a linear polarizer, the maser emission is amplitude modulated. Under normal excitation conditions, for suitable magnetic fields, the maser could oscillate in at least three modes. The maser emission would then consist of a pair of right circularly polarized waves of two different cavity-resonant frequencies and a pair of left circularly polarized waves of different frequencies. In this case, a beat note at the difference frequency is photo-detected without the need of a linear polarizer.

94. Raytheon Co., Research Div., Waltham, Mass., "Spectral Output and Spiking Behavior of Solid-State Lasers," Tang, C. L., H. Statz, and G. DeMars, Journal of Applied Physics, Vol. 34, pp. 2289–2295, August 1963.

Theoretical investigation of the multimode oscillations of solid-state lasers. The spatial variation in the field intensity of the various modes produces nonuniform distributions in the inverted population, and there is little tendency for these distributions to smooth out, because of spatial cross relaxation. Such nonuniform distributions could lead to simultaneous oscillation in many modes. Formulas which relate the number of unstable modes to the pump power and various other maser parameters are obtained. The results show that it is difficult to obtain single-mode operation in conventional masers at high pumping levels. Ways of avoiding a nonuniform distribution density and methods of achieving high-power single-mode operation in practice are discussed. The effect of slow spatial cross relaxation on the spiking behavior is also examined.

95. Ready, J. F. and D. Chen, "Optical Pumping of Masers Using Laser Output," Proceedings of the Institute of Radio Engineers, Vol. 50, pp. 329–330, March 1962.

96. Schwlow, Arthur L., "Optical Masers," Scientific American, Vol. 204, pp. 52–61, June 1961.

97. Shteinshleiger, V. B., G. S. Misezhnikov, and O. A. Afanas'iev, "Efficiency of Various Pumping Systems in Ruby Traveling-Wave Masers," Radiotekhnika i Elektronika, Vol. 7, May 1962, Radio Engineering and Electronic Physics, Vol. 7, pp. 828–833, May 1962 (a Translation).

Comparison between three possible working systems of quantum-mechanical, paramagnetic ruby amplifiers, using a different quantum transition for amplifiers, and a different quantum transition for pumping. The dependence of the amplification coefficient of traveling-wave, quantum mechanical paramagnetic amplifiers on chromium concentration and temperature is investigated in these systems.

98. Siemens und Halske AG, Zentral Laboratorium, Munich, Germany, "Einschwingverhalten Torischer Rubin-Laser in Abhängigkeit von der Pumpleistung," (Initial Oscillation Behavior of Toroidal Ruby Lasers As A Function of Pumping Performance), Hantsche, Harald and Dieter Röss, Zeitschrift für Naturforschung, Vol. 18a, pp. 1020–1021, August/September 1963 (in German).

Presentation of the results of measurements of the damping period, relaxation oscillation, and relaxation period of a toroid of ruby as a function of the pumping performance at various temperatures. The results, shown graphically, demonstrate that the theories of optical single-mode resonators cannot be used to describe the oscillation behavior of the toroidal ruby laser.

99. Siemens and Halske AG, Zentral Laboratorium, Munich, Germany, "Radiofrequency Beats Between Components of Split Axial Modes in Ruby Lasers," Roess, Dieter, Proceedings of IEEE, Vol. 51, pp. 1668–1669, November 1963.

Description of an "exfocal" pumping technique used in experiments on the splitting of axial modes in a ruby laser. The method involves placing the laser and the pumping source symmetric to one another at the respective foci of the major axis of a mirror consisting of an ellipsoid of revolution. For this configuration, the pump light is incident on the laser in exactly rotational symmetry, and if the ruby rod is oriented at 0° to the crystal axis, this leads to rotational-symmetrical absorption of the pump light, and, furthermore, to a symmetrical expansion of the laser during the pumping pulse. This results in periodical relaxation spikes and in a longer duration of the laser emission than in other arrangements.

100. Sorokin, P., G. J. Lasher, I. L. Gelles, "Cross Relaxation and Maser Pumping by a Four Spin Flip Mechanism," Quantum Electronics, Columbia U. Press, New York, pp. 293–297, 1960.

The four spin flip mechanism is discussed. The paramagnetic resonance of nitrogen centers in diamond was studied to determine the existence of this process. For such a mechanism to exist, when T_{n} is much less than the relaxation times of the system, the application of the pump to the center line of the nitrogen spectrum should make the absorption at either satellite drop to zero. If the pump is applied to one of the satellites, the center line absorption should reduce to 3/5 its thermal equilibrium value and the absorption at the other satellite should increase by a factor of 6/5. This behavior was observed at liquid helium temperatures in diamonds containing the largest concentration of nitrogen centers. It is pointed out that the four spin flip transition can be used in special cases to establish cw maser operation by inverting the population of one of the satellite lines.

101. Sperry Gyroscope Co., Great Neck, N.Y., "Lasers: Principles and Uses," Collins, Stuart A., Jr., Electro-Technology, Vol. 71, pp. 64–70, March 1963.

Survey of the theory and applications of solid-state and gaseous lasers. The different types of energy levels in laser ions and atoms are discussed for a ruby laser, a calcium tungstate laser, and a helium-neon laser. Calculation of light intensity from a laser is demonstrated, as is a lens system for improving the collimation of a laser beam. Some laser applications are described for a ruby laser that radiates a 10-kw pulse in red light, and for a neon-helium laser that operates continuously on several frequencies at a power of 3mw. Laser-device modifications based on the use of the laser Q switch, mode selectors, or spike control are noted.

102. Stanford Research Institute, Menlo Park, Calif., "Nondestructive Laser Pumping by High Explosives," Crosby, John K. and R. C. Honey, Applied Optics, Vol. 2, pp. 1339–1340, December 1963.

Description of a technique which allows the light from an explosive light source to pump a laser material without destroying the material. The technique has been demonstrated by pumping a neodymium-doped glass laser from a distance of 3.5 m without damaging the laser. Shown in a figure are the oscilloscope records of photomultiplier output during a shot. The records show that the pump pulse is strong enough to cause this laser to oscillate above threshold. The success of the shot proves that research into ways of improving efficiency and increasing power output of explosively pumped lasers can be performed without sacrificing a laser in each experiment.

103. Stanford University, Calif., "High-Index-of-Refraction Spherical Sheath Composite-Rod Optical Masers," Svelto, O. and M. Di Domenico, Jr., Applied Optics, Vol. 2, pp. 431–439, April 1963. NSF Grant No. G-22929.

Theoretical and experimental investigation of the focusing of pumping light by high index-of-refraction spherical and cylindrical sheaths covering a ruby-rod maser material. The reduction in threshold pumping energy and the increase in optical output energy for the same ruby rod are measured as a function of the index of refraction of the sheath by using spherical and cylindrical sheaths of water and benzyl benzoate. Results clearly show that the spherical sheath is better than the cylindrical sheath. A thermo-dynamical method of analysis is used to develop an approximate three-dimensional theory for the power absorbed per unit volume at each point in the rod. This theory treats the spherical and cylindrical sheath composite-rod structures in a unified way. The theoretical results are in fair agreement with the experiment. The theory shows that the spherical sheath of sapphire is an optimum composite-rod optical-maser configuration. The theory predicts that in this case the threshold pumping energy for maser oscillation should be reduced by a factor of 4, whereas the cylindrical sheath of sapphire should give an improvement by a factor of only 2.4.

104. Stanford University, Dept. of Physics, Stanford, Calif., "Advances in Optical Masers," Schawlow, Arthur L., Scientific American, Vol. 209, pp. 34–35, July 1963.

General review of recent developments in laser research. A description of a typical early ruby laser is given to illustrate the atomic basis of laser action. Among the new developments discussed are semiconductor junction lasers, which promise efficiencies well above 10 percent and possibly approaching 100 percent, compared to the 1 percent efficiency of optically pumped solid state lasers and gas-discharge lasers. Means of achieving high output power are discussed, including the use of a giant-pulse technique capable of delivering a 50 megawatt pulse lasting about 10 nanosec, and an addition to this technique which can produce a peak power output of about 500 million watts in a beam of cross section less than 1 cm. A good lens of focal length 1 cm could focus this beam to spot a thousand of a centimeter in diameter where the beam intensity would be 10^{13} w/cm. Laser beams currently in use can, when properly focused, weld, vaporize or melt a small amount of any substance.

105. Stanford University, W. W. Hansen Labs. of Physics, Microwave Lab., Stanford, Calif., "Pumping Power Considerations in an Optical Maser," Svelto, O., Applied Optics, Vol. 1, pp. 745–751, November 1962.

Investigation of the theoretical efficiency of various pumping power systems that have been adopted in optical masers. A thermodynamical method is used to calculate the power transferred from the flashtube to the active rod. In this way a general expression is obtained which allows the calculation of the total power and the power per unit required from the flashtube, for a given power absorption by the active rod. When the active rod, with an index of refraction equal to n, is covered by a cylindrical sheath with the same index of refraction, then (1) the power per unit area required from the flashtube for a given power absorption of the rod is at best n times lower than in the case of a simple rod, and (2) the total power required from the flashtube is, however, the same in both cases. The rod covered by a sheath is not the most efficient system. The theory, in fact, shows that the most efficient system is obtained by allowing the pumping power to enter the active rod from all possible directions. In such a case the power per unit area required from the flashtube is n^2 times lower than in the case of a simple rod.

106. State Optical Institute, Leningrad, USSR, "Operation of a Four-Level Optical Quantum Generator," Anan'ev, Iu. A., V. F. Egorova, A. A. Mak, D. S. Prilezhaev, and B. M. Sedov, Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki, Vol. 44, pp. 1884–1888, June 1963, Soviet Physics —JETP, Vol. 17, pp. 1268–1270, December 1963, (a Translation).

Theoretical and experimental investigation of the effect, on the properties of an optical quantum generator (laser), of the working substance, the parameters of the resonator, and the pump intensity based on the steady-state theory of a four-level laser. An equation is developed which shows that the optimum value for transmission depends on the loss in the crystal and on the pump power. In order to check this, the dependence of threshold power and generated power in $CaF_2:U^{3+}$ and $CaF_2:Sm^{2+}$ lasers on the crystal temperature and the reflection coefficient of the resonator mirror was investigated, as was the dependence of the generated power on the pumping power. The experiments were carried out on cylindrically-shaped crystals whose end surfaces were covered with a dielectric reflecting layer. The results of the experiments show that the elementary theory of steady-state generation developed, satisfactorily describes the principal features of a four-level laser.

107. Technical Research Group, Inc., Melville, N.Y., "Research on Properties of Laser Devices," Fifth Quarterly Technical Summary Report, June 1963–August 1963, Rothberg, S., ed., TRG-134-QTR-5, 1963, Contract AF 49(638)873, ARPA Order 356-62, Project Defender.

The limitations on power and efficiency of gas lasers were analyzed. Lamp and laser tube construction including provision for pumping of the CsBr photodissociation laser has been completed. A preliminary literature search for transition metal molecules suitable for high-power gas lasers was carried out. The development of apparatus for the nuclear fission pumping of solid-state media is continuing. Various crystalline and noncrystalline media containing rare-earth elements have been prepared. The action of the Lummer-Gehrcke plate Q-switch has been successfully demonstrated. The angular brightness measurements of the He-Ne laser were made as a function of cavity length for a sphere flat resonator.

108. Technical Research Group, Syosset, N.Y., "Research on Properties of Laser Devices," Quarter technical summary Rept. No. 3, December 1962–February 1963, Newstein, M. and S. Rothberg, eds., Rept. No. TRG-134-QTR-3, February 1963, AD-400 154, Contract AF 49(638)673.

Analytic work continued on the study of the variation of the power output versus frequency for a doppler line shape, and on the modes of laser cavities. Oscillation at 3.2 mu has been achieved in the optically pumped Cs laser in a sealed-off cell. The study of the possibility of utilizing photodissociated T1Br as a gaseous laser medium was pursued. Crystalline and glassy media for rare-earth ions were studied. Oscillation has been achieved in prism cavities formed by a corner-cube reflector facing either a flat or another corner-cube. Results are presented of a study directed toward maximizing the over-all efficiency and angular brightness of mechanically Q-switched ruby oscillators.

109. Technical Research Group, Syosset, N.Y., "Research on Properties of Laser Devices," Quarterly technical summary Rept. No. 4, March 1963–May 1963, Newstein, M. and S. Rothberg, TRG-134-QTR-4, May 1963, AD-411 950, Contract AF 49 638 673, ARPA Order 356 62; Project 7300.

Theoretical study of the performance of pulse oscillators was continued. Qualitative agreement was obtained with results of experiments dealing with the effects of varying cavity time constant and scattering loss. Crystalline and glassy media for rare-earth ions were studied. Work on laser pumping by the photodissociation of molecules was Continued and extended to include CsBr and CsI in addition to T1Br. Work on the metastable transition laser was begun. The noise power spectrum of a laser was investigated. Oscillation was achieved in more lasers with retroreflecting prism cavities and their properties investigated. The study of Q-switched lasers was continued and a new faster mechanical Q-switch was designed. Experiments to investigate the possible existence of a fundamental limit to the maximum angular brightness of a laser were initiated.

110. Texas Instruments, Inc., Dallas, Tex., "Performance of a Continuous-Wave Neodymium Laser," Keck, P. H., J. J. Redmann, C. E. White, and D. E. Bowen, Applied Optics, Vol. 2, pp. 833–837, August 1963.

A high-pressure compact xenon arc lamp with an ellipsoidal collector of 61 cm diameter and an opening of f/0.4 served as pumping source. The flux available from this source is concentrated into the 2 x 2 x 12 mm laser rods of neodymium-doped calcium tungstate by either a straight cone condenser or by a chisel-shaped condenser. Both condenser designs are discussed. Continuous laser action has been achieved for periods up to more than one hour, using water cooling at room temperature.

111. Tohoku University, Sendai, Japan, "Possibility of Optical Cooling of Ruby," Tsujikawa, Ikuji and Tsuyoshi Murao, Journal of the Physical Society of Japan, Vol. 18, pp. 503–510, April 1963.

Estimation of cooling rates and cooling capacities of a ruby. It is shown that when Cr^{3+} ions in ruby are optically pumped by photons with a given energy and emit photons with higher energies, the lattice energy can be extracted as light so that a cooling effect appears. If some possible heating effects do not overcome this cooling effect, the temperature will actually be reduced. Cooling rates and cooling capacities are given. Technical problems and possible heating effects are discussed.

112. Tokoyo Institute of Technology, Japan, "Experiment on Quasi-Fundamental Mode Oscillation of Ruby Laser," Suematsu, Yasuharu and Kenichi Iga, Proceedings of IEEE, Vol. 52, pp. 87–88, January 1964.

Measurement of the radiation angles of the output light associated with a ruby rod with dielectric multilayer plane reflectors on the whole area at both ends of the rod. The results are compared with the calculated values using relations between a radiation angle and the pumping energy of a ruby laser. Transverse fundamental mode oscillations are obtained by restricting the diameter of one of the reflectors within approximately one order smaller than that of the rod.

113. U.S. Army Electronics Research & Development Labs., Fort Monmouth, N.J., "Bibliography on Optical Masers and Related Subjects," Poultney, S. K., Solid/State/Design, Vol. 4, No. 11, pp. 49–64, November 1963 and also Vol. 5, No. 1, pp. 36–48, January 1964.

114. U.S. Army, Signal Research and Development Lab., Fort Monmouth, N.J., "A Method for Evaluating Laser Potentialities of Crystals," Theissing, H. H., P. J. Caplan, T. Ewanizky, and G. de Lhery, Applied Optics, Vol. 2, pp. 291–297, March 1963.

Description of optical measurements of a laser figure of merit with reference to a particular pumping device in order to evaluate the laser potentialities of various crystals, or to compare one crystal with another of changed composition and concentration. It is pointed out that these measurements can be performed on slabs without laser end faces. They can be carried out by irradiation with white light in which the fluorescence wavelength under study is suppressed. If optical apparatus for this selective band suppression is not available, the evaluation of the figure of merit is shown for monochromatic irradiation.

115. U.S. Naval Ordnance Lab., Corona, Calif., "Argon Tube Pumped Laser," Long, Leslie T. and Robert L. Conger, Applied Optics, Vol. 3, p. 156, January 1964.

Experimental investigation which demonstrates that gas discharge tubes filled with argon gas are at least as effective as xenon discharge tubes for pumping a ruby laser. For the experiment, two U-shaped tubes were placed beside a sapphire overcoated ruby rod. The two tubes and the ruby were wrapped with aluminum foil. It was found that, when the U-shaped discharge tubes contained argon, the laser threshold was the same as when the tubes were filled with xenon. The output of the ruby laser as observed by a phototube and oscilloscope appeared the same with either xenon or argon.

116. Utah University, Microwave Devices Lab., Salt Lake City, "Irradiated Laser Materials," Johnson, V. R. and R. W. Grow, Consolidated Quarterly Rept. pp. 42–44, 31 March 1963, See N63-18701 17-09, NSF Grant 15017.

Progress is reported on a project designed to investigate the possibility of reducing the pumping energy required for a solid-state ruby laser by γ-ray damage and by applying extremely high static pressure. A nitrogen-cooled ruby rod in elliptical laser cavity apparatus was constructed and tried. The apparatus proved unsuccessful. The rod was next γ-irradiated at room temperature for

periods of the order of 15 to 25 hours. This amount of irradiation was sufficient to snuff out laser action in the crystal, at least for the input pump power available. The γ-damage in ruby was found to be annealed out by heating the crystal to about 400°C and at least partially annealed by optically pumping the crystal in a laser configuration.

117. Varian Associates, Palo Alto, Calif., "A Proposal for a DC Pumped Rare-Earth Laser," Bell, R. L., Journal of Applied Physics, Vol. 34, pp. 1563–1564, May 1963.

Development of a method for minimizing the losses inherent in the collection and transmission of pumping radiation in the conventional laser. The method uses the recombination radiation to raise impurity centers in the host to optically excited states which could then be lased (normally at photon energies less than the band gap). A figure shows the elements of the scheme. It is stated that a major advantage of this scheme over the recombination laser is that the photon energy may be much lower than the absorption edge for the large band-to-band absorption of the lattice.

118. Watkins-Johnson Co., Palo Alto, California, "Research and Investigation of Materials for Laser Applications," Interim Engineering Report No. 3, 1 January 1963–31 March 1963. Fitzpatrick, R. and S. E. Sobottka, Rept. W–J 63–612R12, 1963, Contract AF 33(657)–8917.

Light emission from pulsed diodes made of Nd doped GaAs and from undoped GaAs diode lasers was investigated. For the Nd doped diode studies, two different doped GaAs samples were used. One of a single crystal material containing an amount of Nd determined by independent analysis to be about 0.01 percent, and one of poly-crystalline material containing about 0.7 percent Nd distributed in an unknown manner. Emission measurements of Nd doped diodes revealed lines in the range of 0.1μ to 1.1μ. These lines were not observed with five undoped GaAs diodes and were therefore indicated to be Nd emission lines. This is apparently the first time that emission from rare-earth ions has been reported. This emission indicates that the dc excitation of rare-earth centers in semiconductors is possible, as was originally predicted. Therefore the possibility of a low-threshold dc-pumped laser using rare-earth doped semiconductors seems assured. Also, diodes from GaAs without Nd have been fabricated according to techniques designed to optimize laser action. Studies of the emission of these diodes, integrated over-all wavelengths, have been made as a function of current, up to 10 amps peak, with the diode immersed in liquid N_2. Results indicate that laser action occurs at peak currents above a few amps (current density about 10^3 am/cm^2).

119. Watkins-Johnson Co., Palo Alto, Calif., "Energy and Power Considerations in Injection and Optically Pumped Lasers," Appendix-Optimum Coupling in Three-Level Lasers," Yariv, Amnon, Proceedings of IEEE, Vol. 51, pp. 1723–1731, December 1963.

Review of the principles and techniques of power and energy in lasers. Both three- and four-level lasers are considered in the pulsed and continuous modes of operation. The theoretical power and energy estimates are compared with experimental data.

120. Westinghouse Electric Corp., Research Labs., Pittsburgh, Pa., "Optical Pumping of Lasers Using Exploding Wires," Church, Charles H., R. D. Haun, Jr., T. A. Osial, and E. V. Somers, Applied Optics, Vol. 2, pp. 451–452, April 1963.

Description of several experiments on the optical pumping of lasers. It is found that the exploding wire allows much higher pumping rates than flash lamps. As a source of light, in the visible spectrum the wire appears to be less efficient. It is noted that the efficiency of the wire for pumping lasers could be enhanced appreciably by a better choice of laser conditions, together with improved coupling to the laser rod of the light emitted by the plasma.

121. Westinghouse Research Labs., Pittsburgh, Pa., "Coaxial Laser Pump," Church, Charles H., Derek Ryan and James P. Lesnick, Paper presented at the 1963 Spring Meeting of the Optical Society of America, Jacksonville, Fla.

The annular discharge or coaxial flash lamps offer certain advantages for high-energy optical pumping of lasers. The lamps can be made mechanically strong, and they also allow a large radiative area with a moderate emitting-layer thickness. A study has been made of the radiant energies emitted by these lamps filled with rare gases at various pressures for current pulses of varying magnitude and duration. The energy inputs to the lamps ranged from 10 to 25 kJ with quarter-cycle discharge times of less than one millisecond. The effect of changes in the annular spacing upon the lamp output was also investigated. The apparatus and techniques used will be described, and a discussion of the results will be presented with particular emphasis on this form of lamp as a pump source for lasers.

122. Westinghouse Electric Corp., Research Labs., Quantum Electronics Dept. Pittsburgh, Pa., "Laser Materials and Devices—A Research Report," Haun, R. D., Electro-Technology, Vol. 72, pp. 63–71, September 1963.

Summary of developments in laser materials and devices. Enumerated are the properties required of a material to be capable of laser action, the parameters of laser performance, and the individual properties of laser materials. Several different means of laser classification are considered in detail: grouping according to the state of matter of the laser medium, according to the excitation scheme, or according to the active ion or molecule producing the laser action. Future means of perfecting present laser devices are discussed, as well as the selection of new materials, such as Cr^{4+} and CaF_2:Dy^{2+}.

123. Wheeler Labs., Great Neck, N. Y., "The Pump-Power Chart for Evaluation of Modes in a Laser Oscillator," Kaplan, Robert A., Presented at the Symposium on Optical Masers, Polytechnic Institute of Brooklyn, April 16–19, 1963.

The output of a laser oscillator comprises radiation from one or more modes of the resonator, where each mode represents a particular, stable field configuration. Each mode provides radiation in a specific off-axial direction at a specific resonant wavelength; therefore, a knowledge of these modes provides information on the total beamwidth and bandwidth of the laser oscillator. A graphical method of approximately determining the modes in which oscillation may occur and the resultant laser performance has been developed.

124. Wheeler Labs., Great Neck, N. Y., "Designing Lasers with Pump-Power Charts," Kaplan, Robert A., Electronics, Vol. 36, pp. 23–28, 27 December 1963.

Description of a graphical method, using pump-power charts, which relates pump power, wavelength, and propagation direction of a laser. As a first step, the modes of the resonator are plotted on a mode chart in terms of the direction of propagation and of the resonant wavelength of the plane waves comprising those modes. The relations between threshold pump power and these factors appear as contours on the chart, forming the pump-power chart. This chart permits the determination of laser oscillation modes at a given pump level in terms of wavelength and direction of propagation, and, thereby, permits the determination of the frequency and angular spectra of the emitted radiation. In particular, the total bandwidth of the laser output may be obtained directly.

125. Yale University, Sloan Physics Lab., New Haven, Conn., "Disassociative Excitation Transfer and Optical Maser Oscillation in Gas Discharges," Bennett, W. R., Jr., Paper presented at the 16th Northeast Electronic Res. and Engineering Meeting, 5–7 November 1962, Boston, Mass.

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Redstone Scientific Information Center Directorate of Research and Development U. S. Army Missile Command Redstone Arsenal, Alabama	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

LASERS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(Last name, first name, initial)*

Caras, Gus J.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1964	40	125

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	RSIC-195
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	AD ________

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Same as No. 1

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This state-of-the-art survey consists of two sections, a technical summary and a bibliography. Although the bibliography, which consists of 125 references and covers the period of 1 January 1963 to 31 December 1963 deals mostly with the subject of laser pumping, the summary reviews other topics of laser technology including a description of the various types of lasers and their potential applications.

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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